Electric dipole excitation of nuclei studied by proton scattering

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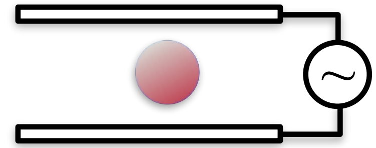
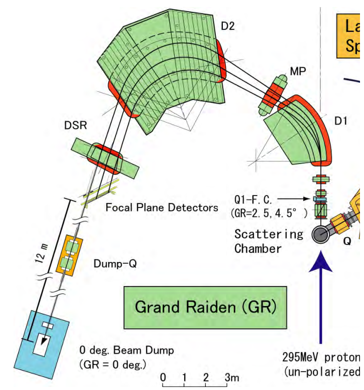
May 23-27, 2022 at Kyoto

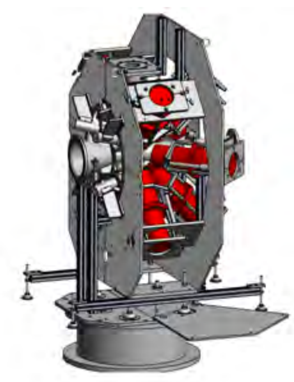
Outline



I. Electric Dipole Response of Nuclei

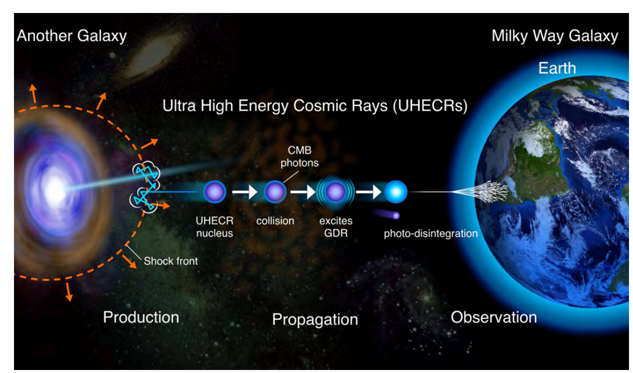


II. Experimental Methods



III. Topics

- Polarizability and Symmetry Energy
- Gamma Decay of GDR
- PANDORA project
  Ultra-High-Energy Cosmic Rays



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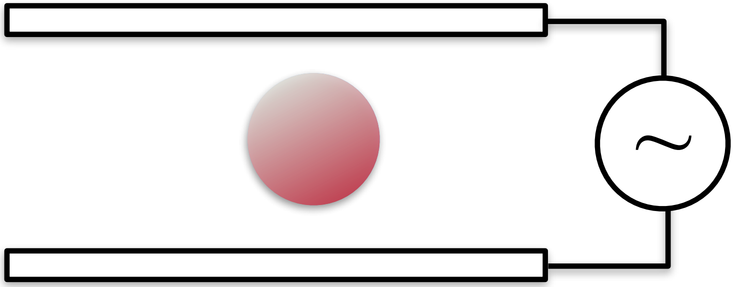
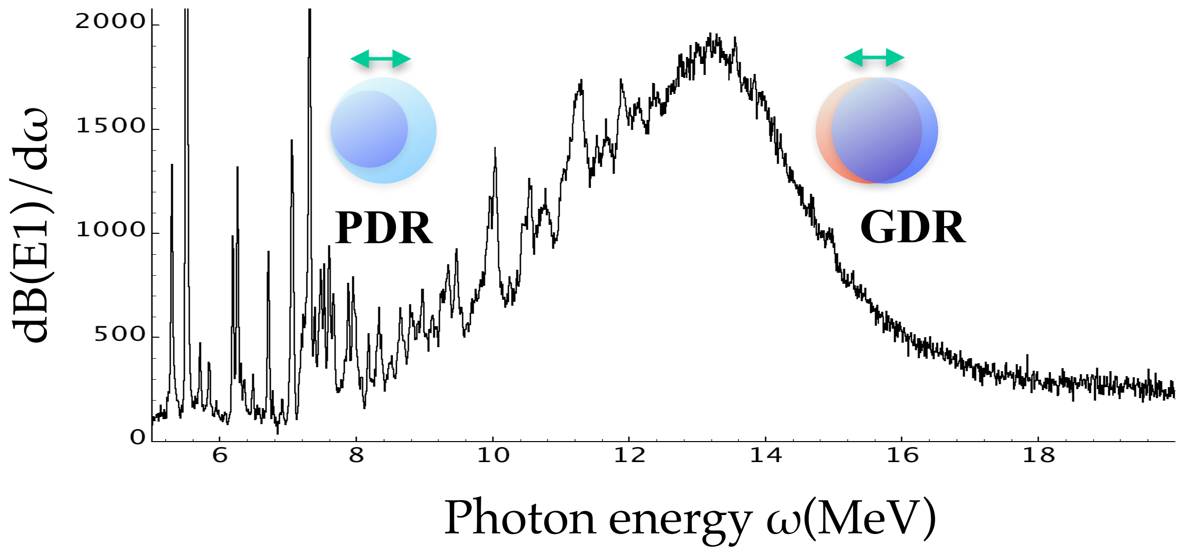
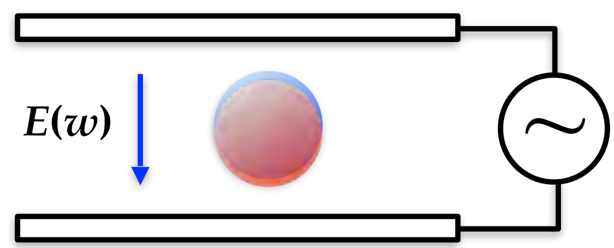


Electric Dipole Response of Nuclei



Inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{dB(E1)}{E_x}$$



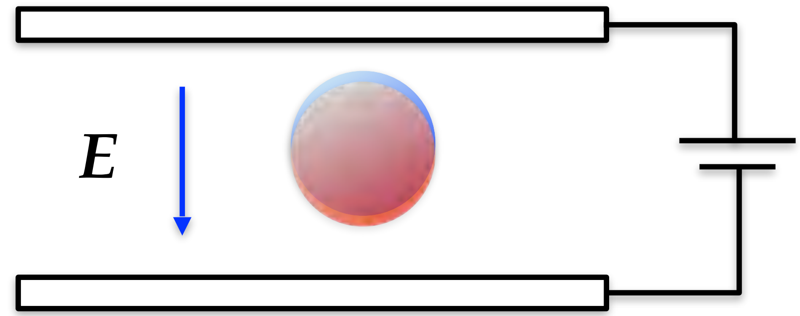
first order perturbation calc. A.B. Migdal: 1944

Static Electric Dipole Polarizability (α_D)

Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability

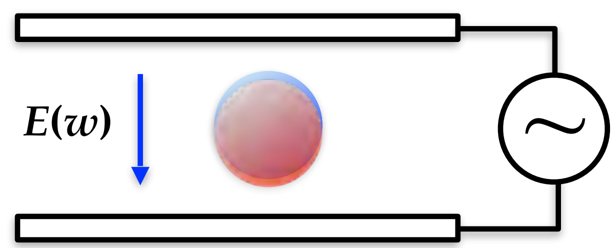


The **restoring force** originates from the **symmetry energy.**

nucleus
in a static electric field
with fixing the c.m. position

Inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{dB(E1)}{E_x}$$



first order perturbation calc. A.B. Migdal: 1944

Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

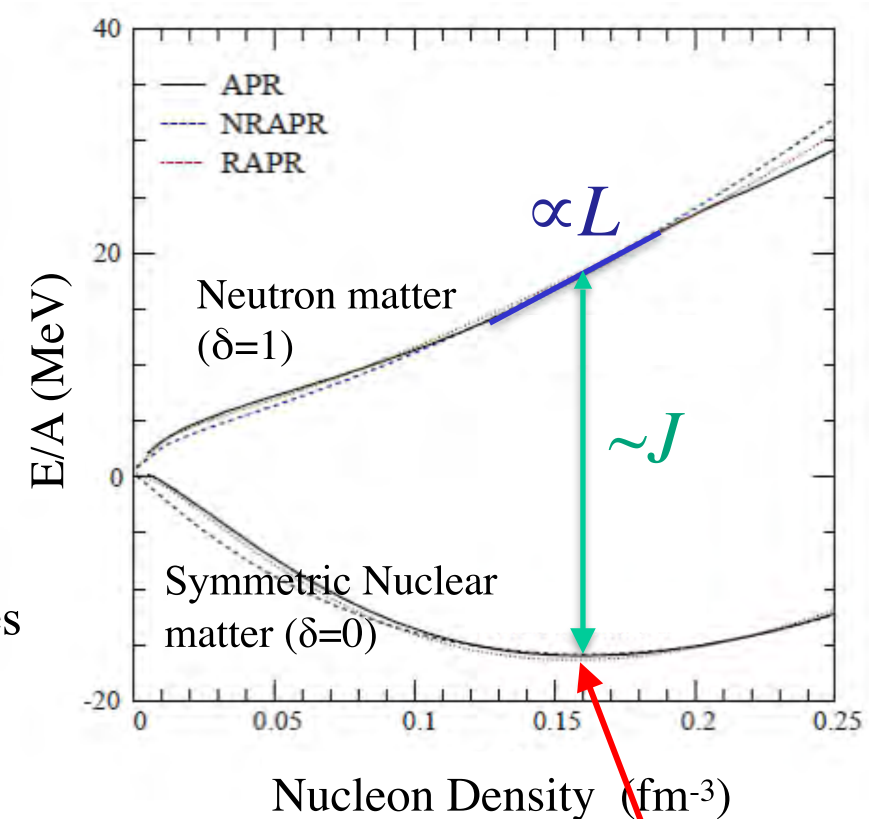
$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\delta^2+\cdots$$

$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho_0)+\ldots$$

Density difference between *n* and *p* increases the system energy by the symmetry energy.



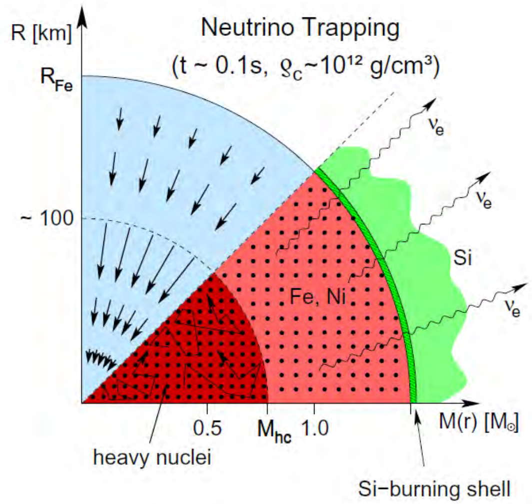
Saturation Density ρ_0

~ 0.16 fm^{-3}

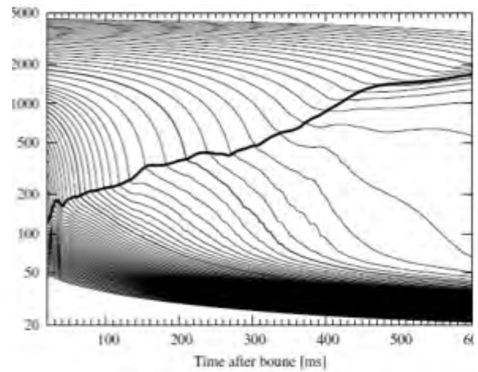
Symmetry Energy of the Nuclear EOS

is fundamental information for stellar processes

Core-collapse supernova



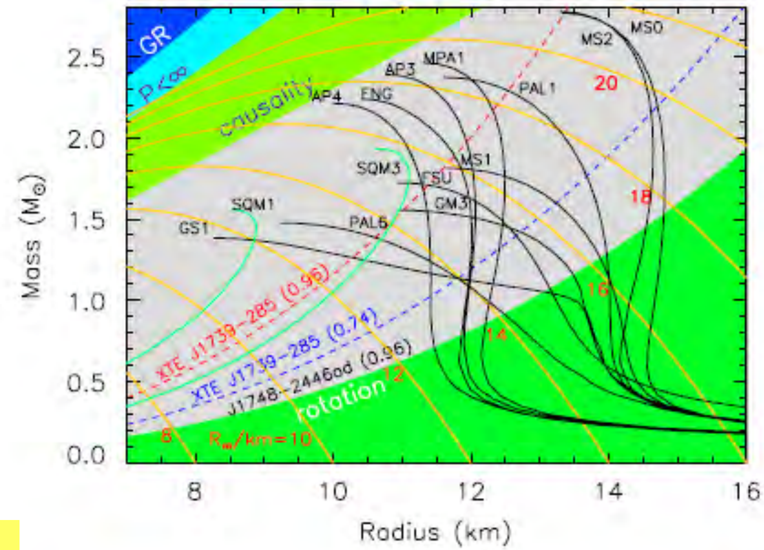
Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

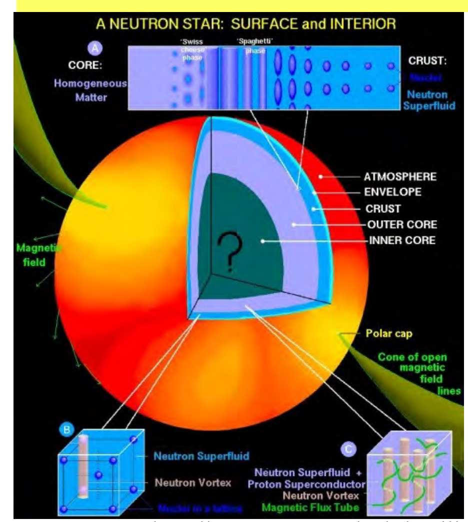
Nucleosynthesis

Neutron star mass vs radius



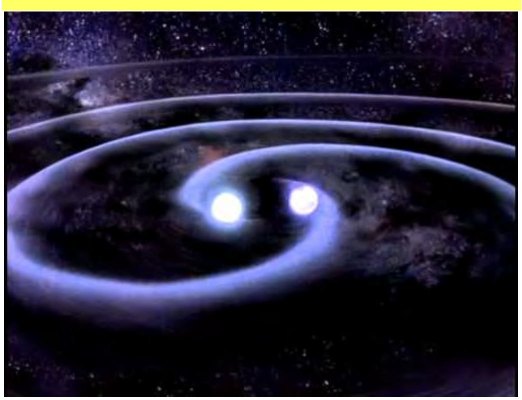
Lattimer et al., Phys. Rep. 442, 109(2007)

Neutron star structure

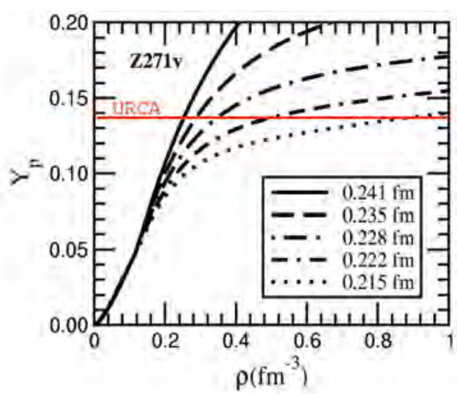


http://www.astro.umd.edu/~miller/nstar.html

Neutron Star Merger Gravitational Wave

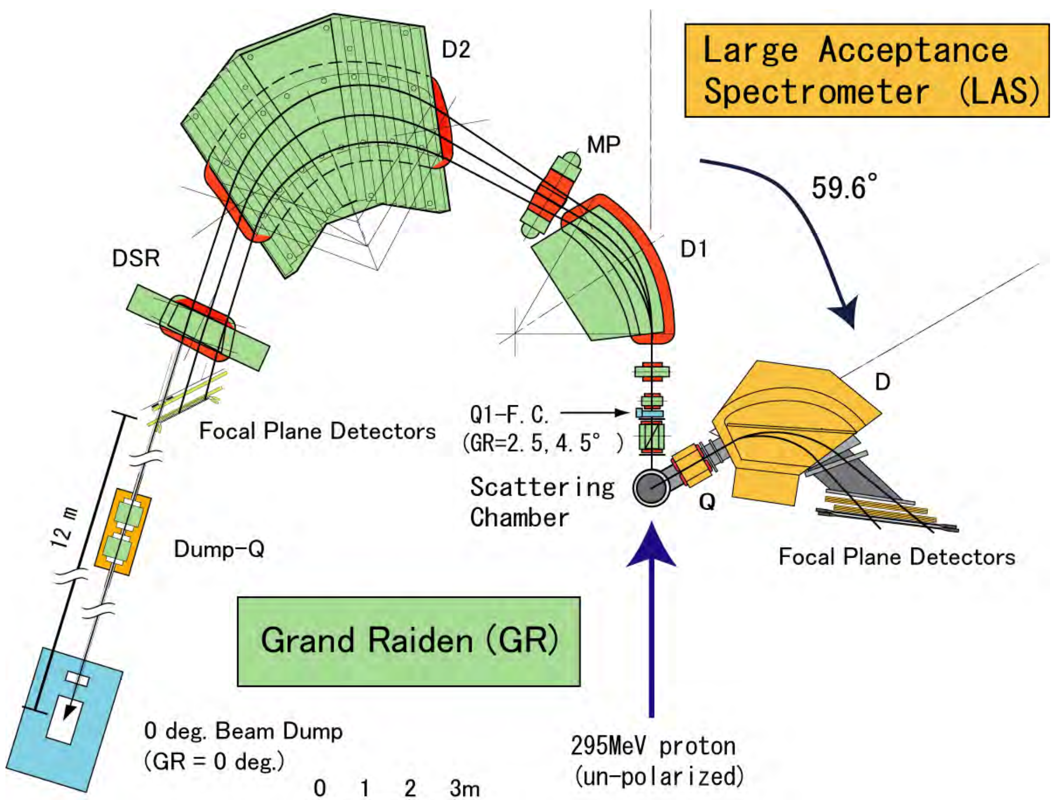

https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



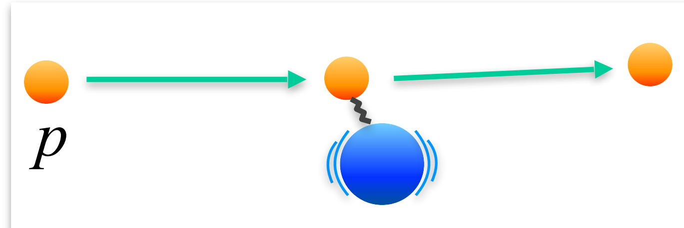
Lattimer and Prakash, Science 304, 536 (2004).

II Experimental Methods



Probes for the Electric Dipole Response of Nuclei

1. Virtual photon excitation
   (Coulomb excitation)
   - proton inelastic scattering at 0 deg.



Proton beams at RCNP and iThemba LABS

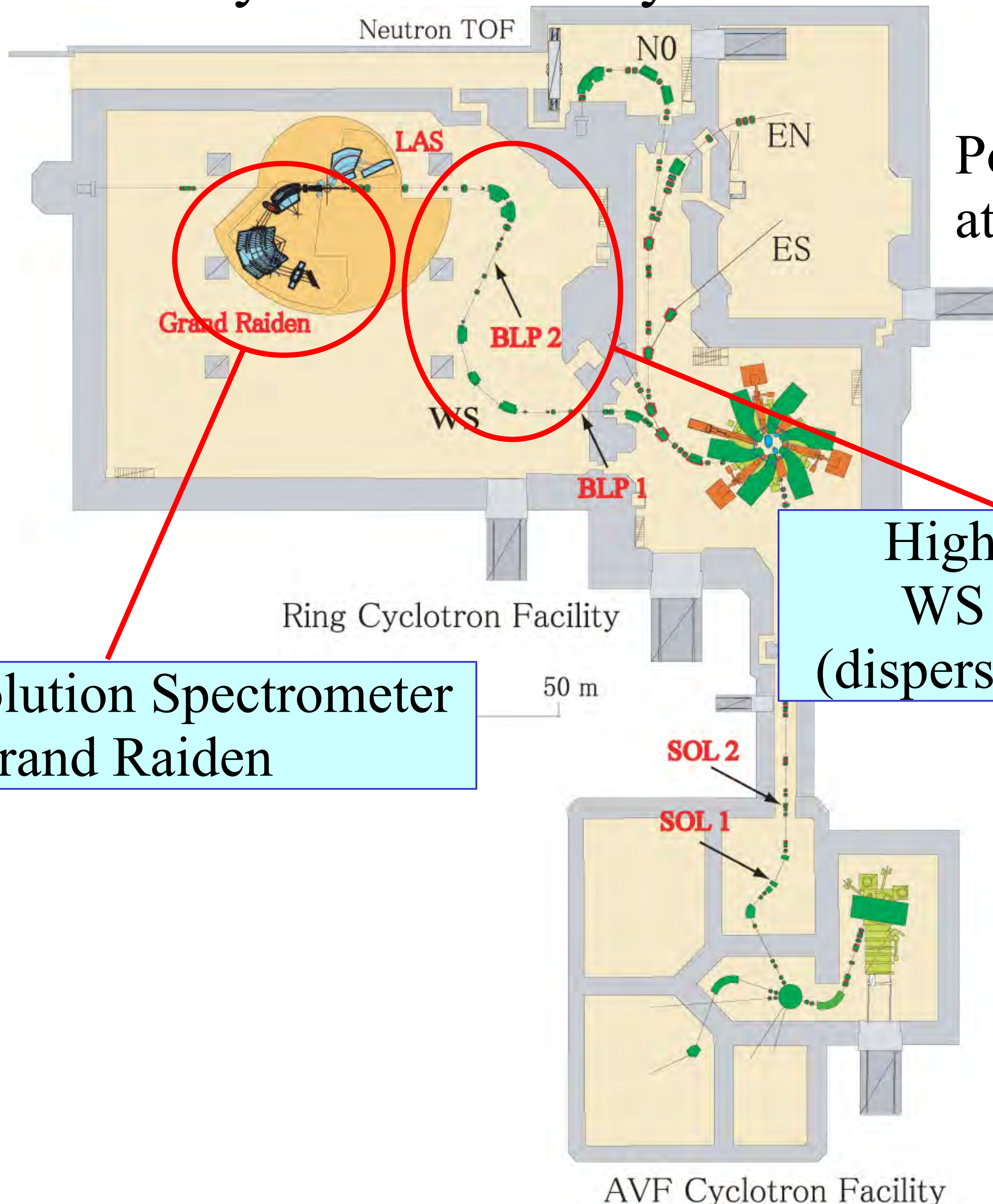
dominantly electric excitation: req. decomposition
E_x distribution is obtained in one shot
sensitive to the total strength

2. Real photon absorption
   - (γ,γ’) Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … photodisintegrations

Real γ-beam at ELI-NP

pure EM probe by quasi-monoenergetic γ
precise absolute strength
partial strength for each decay channel including *n*
clear selection of E1 and M1 (polarized-gamma)

Cyclotron Facility at RCNP



Polarized p beam at 295 MeV

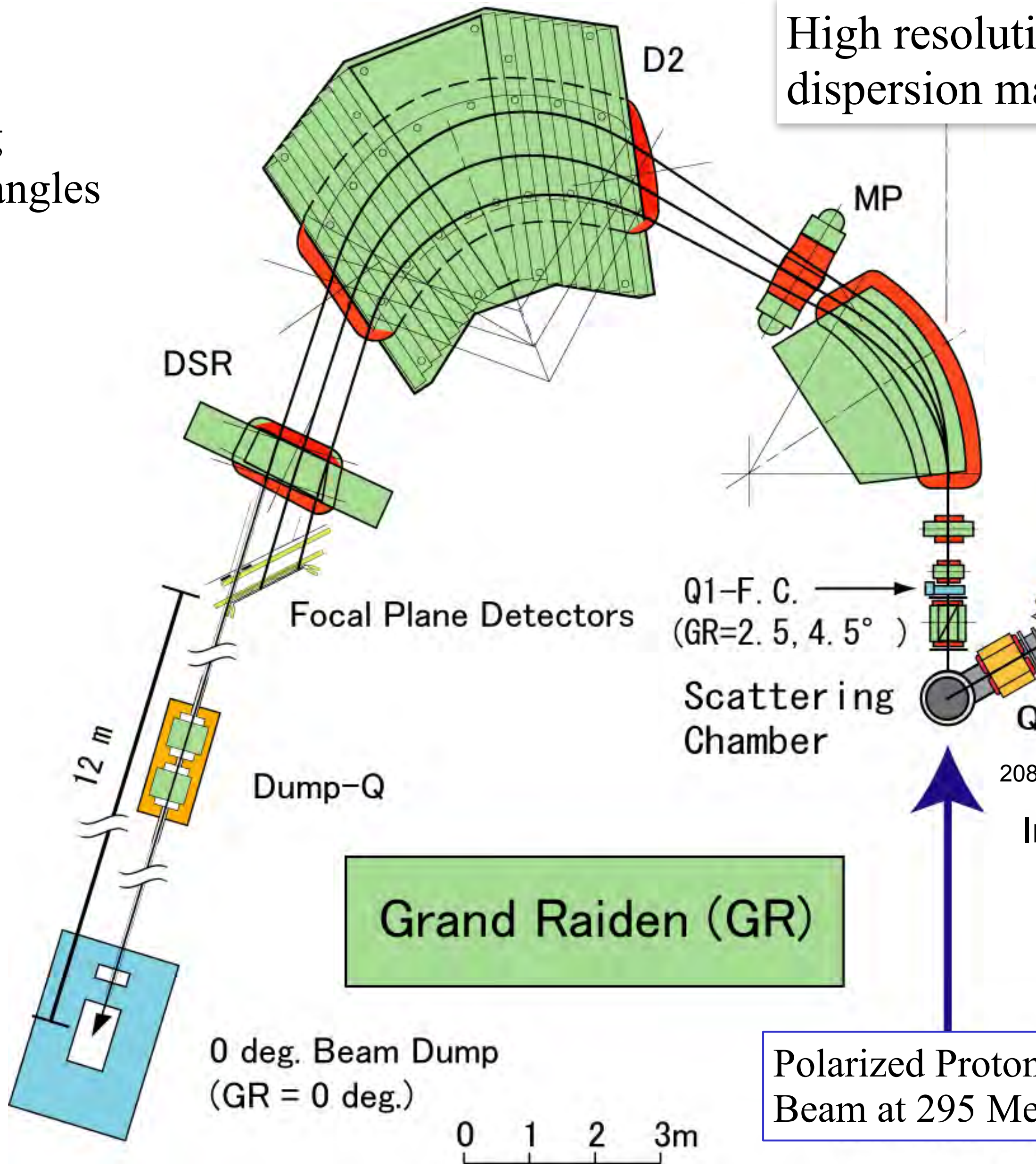
High-resolution
WS beam-line
(dispersion matching)

High-resolution Spectrometer
Grand Raiden

High-Resolution Spectrometer "Grand Raiden"

Proton scattering
at very forward angles

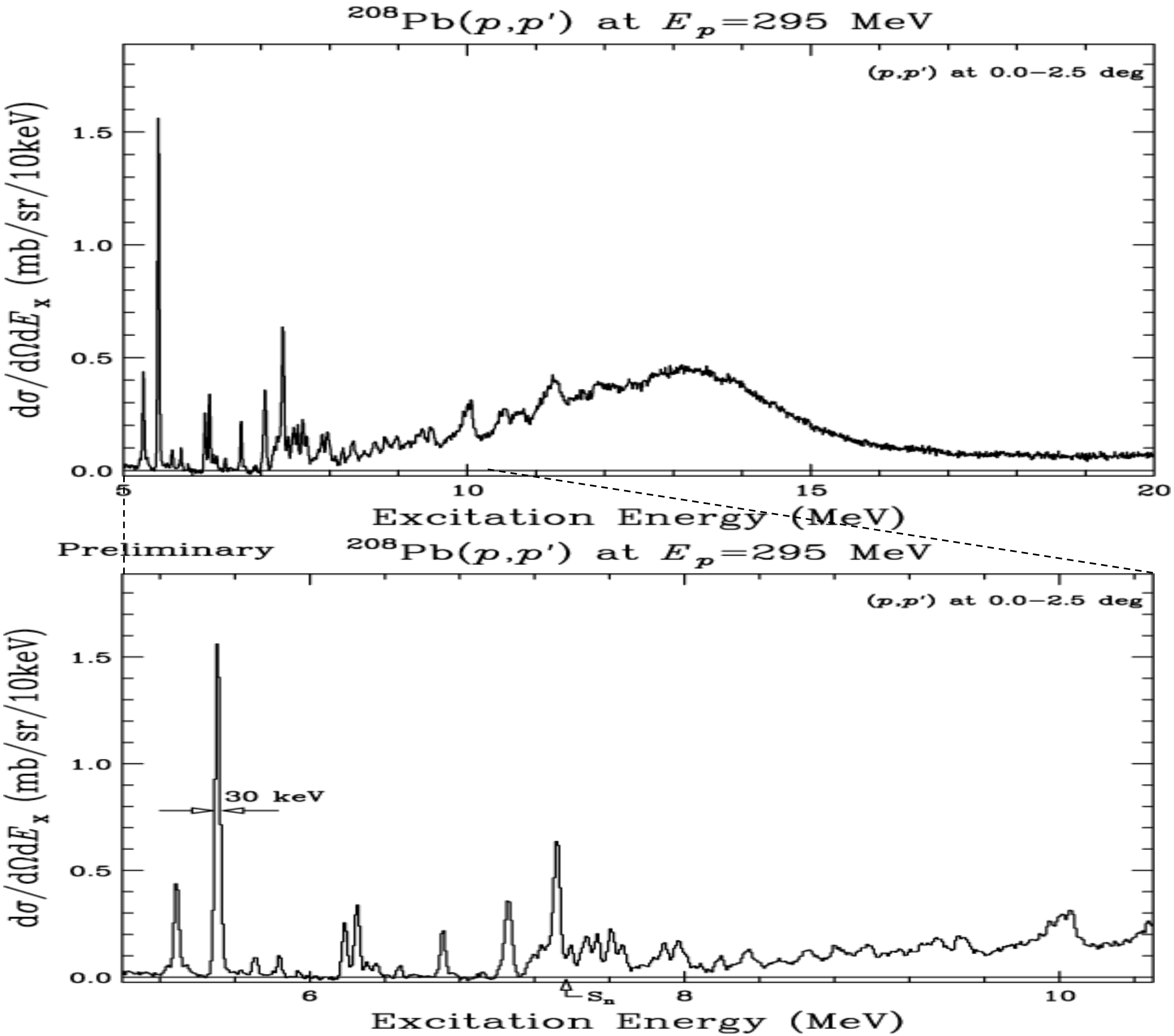
High resolution of 20-30 keV:
dispersion matching.



^{208}Pb target: 5.2 mg/cm^2
Intensity : 1-8 nA

Polarized Proton
Beam at 295 MeV

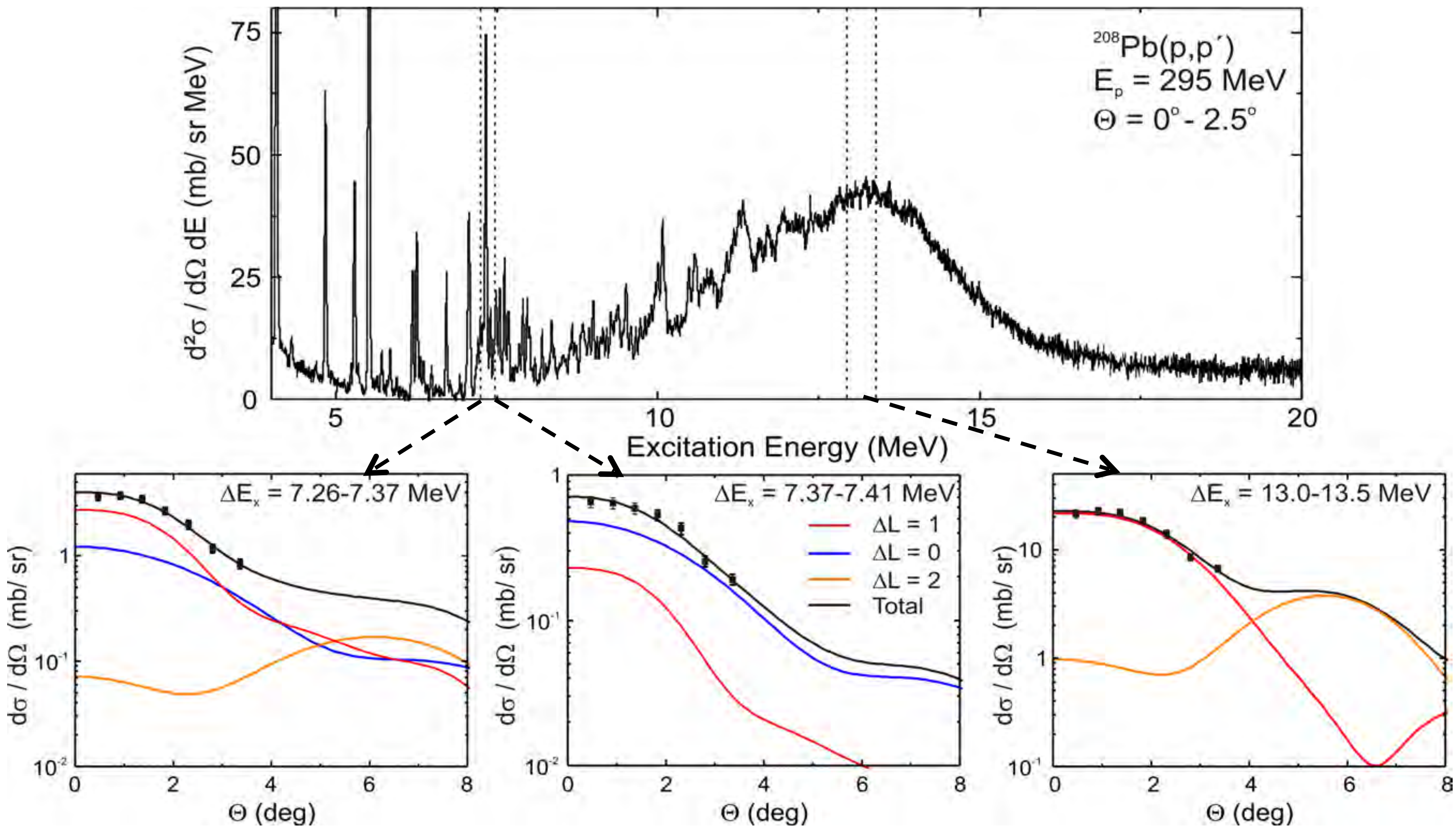
AT et al., NIMA605, 326 (2009)



^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE$_x$ (mb/sr/10keV)
1.5
1.0
0.5
0.0
5
10
15
20
Excitation Energy (MeV)
Preliminary
^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE$_x$ (mb/sr/10keV)
30 keV
1.5
1.0
0.5
0.0
6
8
10
S$_n$
Excitation Energy (MeV)

B(E1): continuum and GDR region

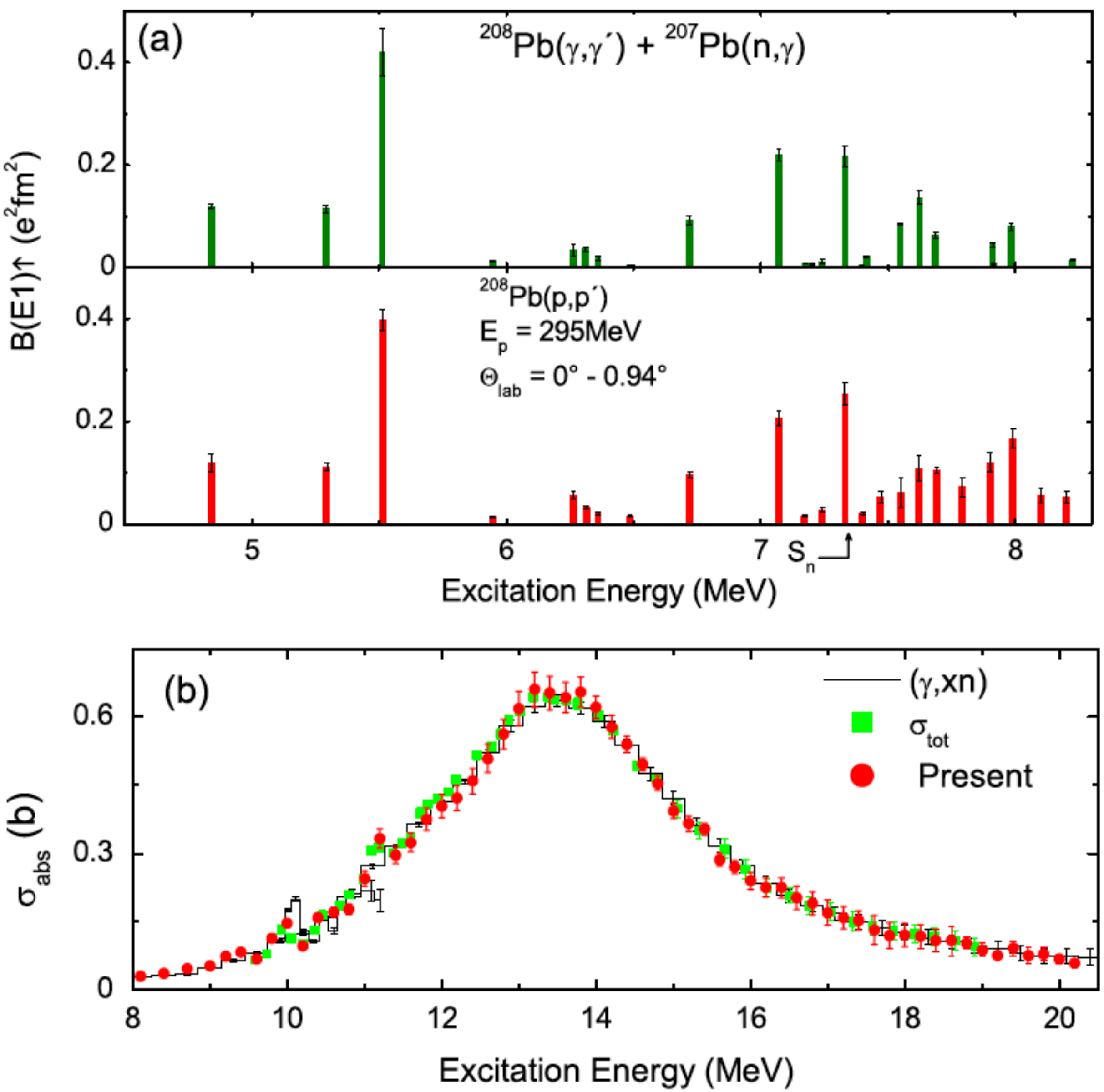
Multipole Decomposition Analysis (MDA)



- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

Comparison with (γ,γ') and (γ,xn)

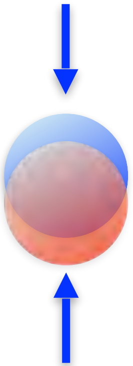


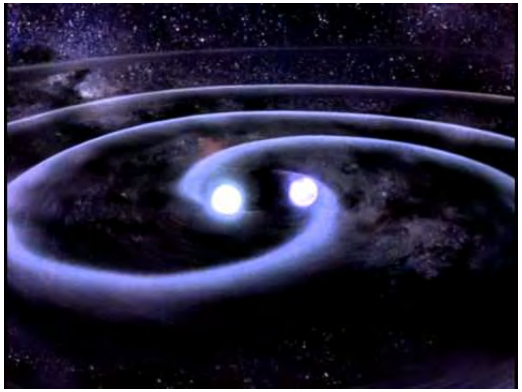
low-lying discrete states

GDR region

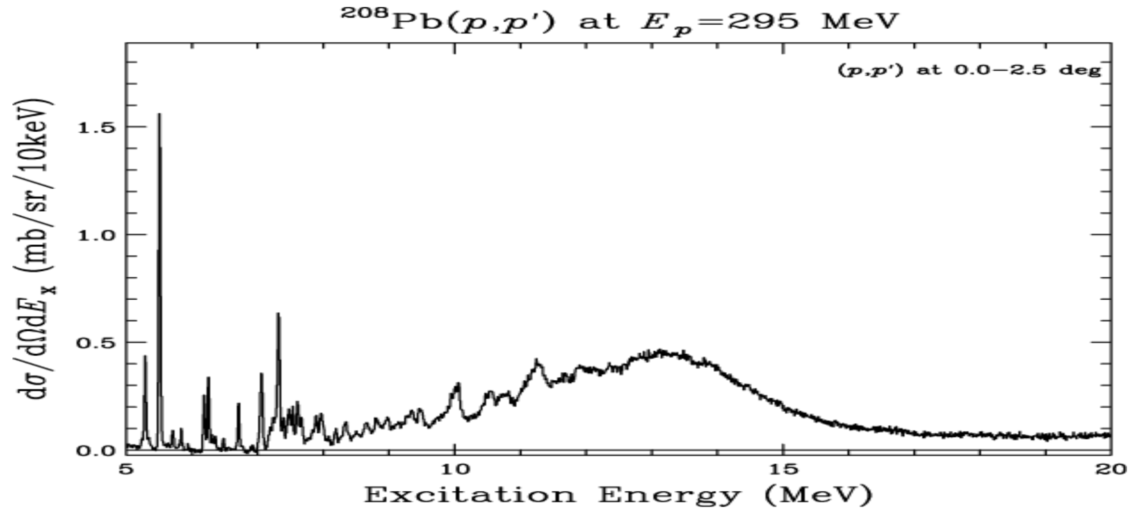
III Topics

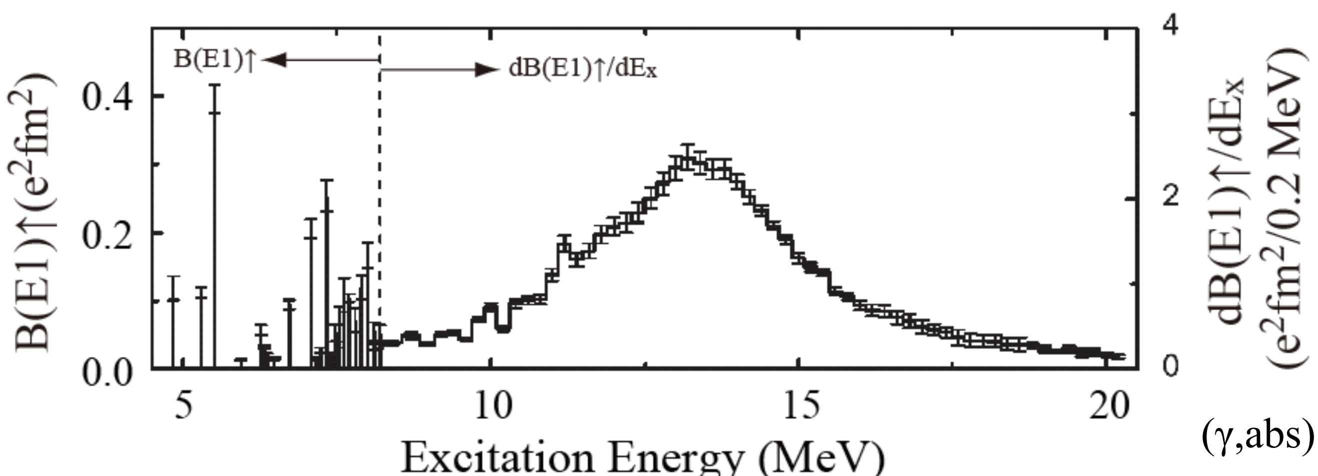
Polarizability and Symmetry Energy





Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn

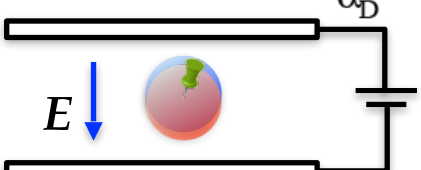




(γ,abs) at Mainz

E_x	0	10	20	130 MeV
α_D	2.7	16.2		1.2 fm³

total 20.1±0.6 fm³

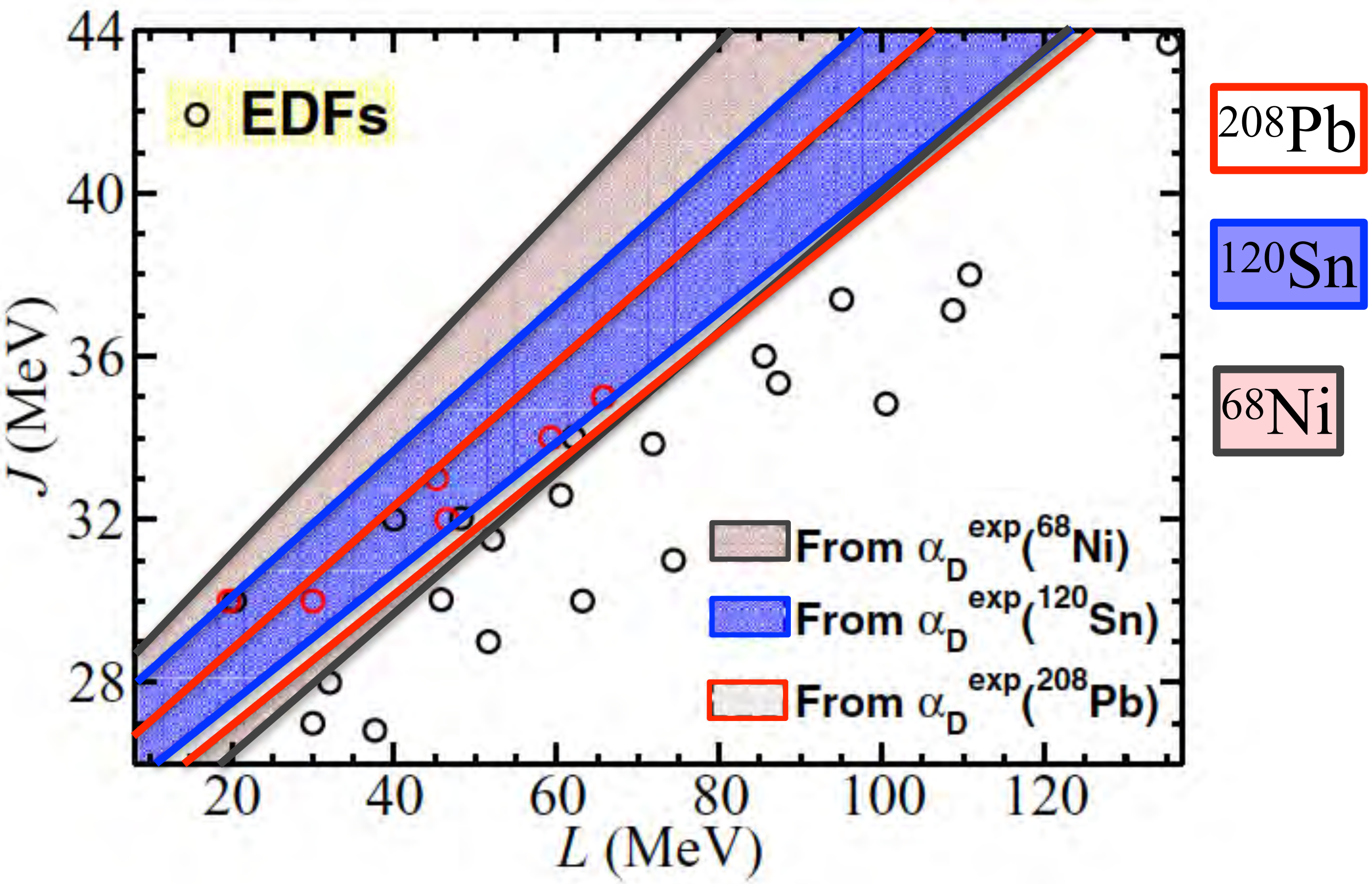


$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

AT et al., PRL107, 062502(2011)

Constraints on *J*-*L* from the EDP data

X. Roca-Maza et al., PRC92, 064304(2015)

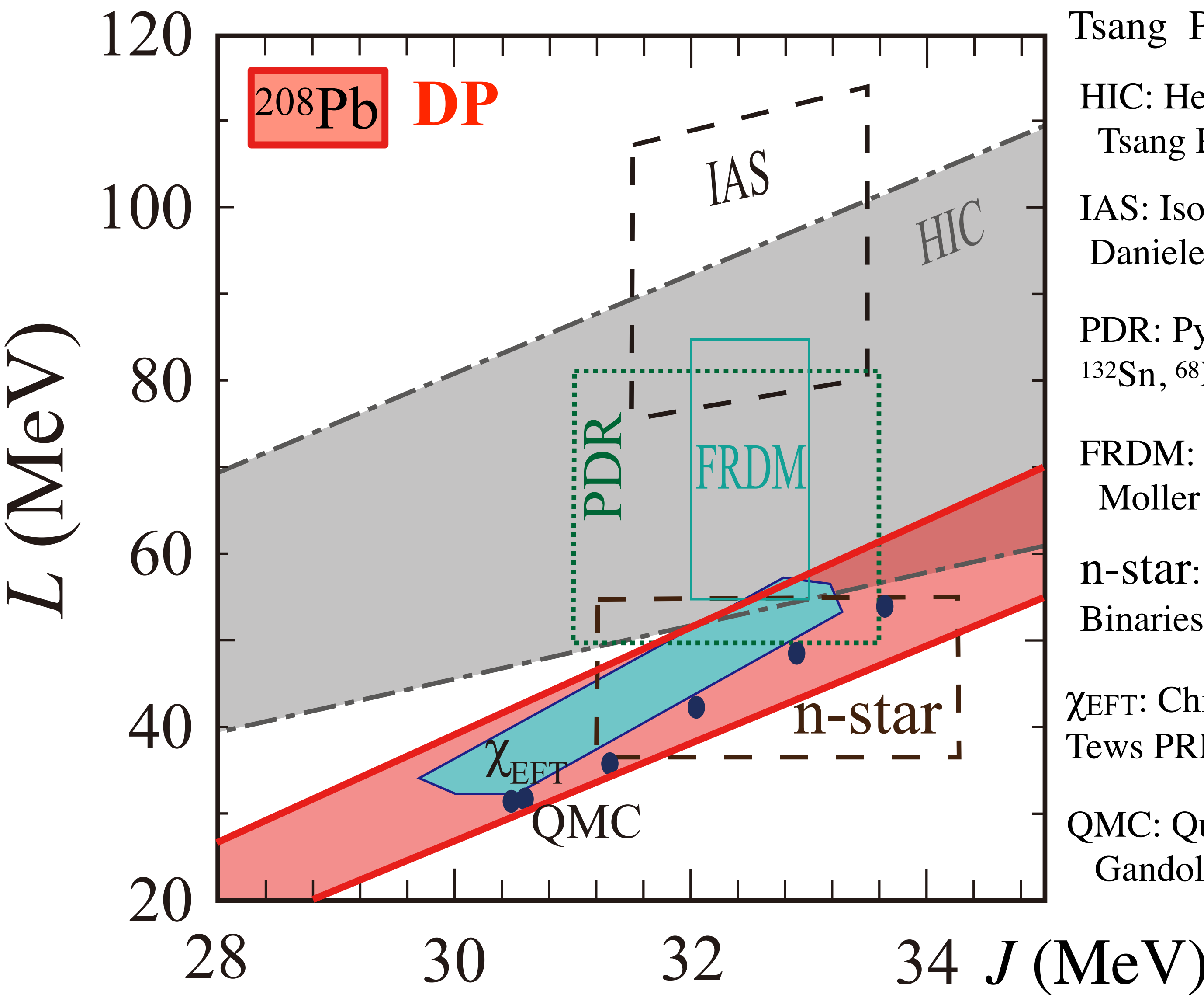


RCNP ^{208}Pb: AT *et al.*, PRL**107**, 062502 (2011).

RCNP ^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).

GSI ^{68}Ni: D.M. Rossi *et al.*, PRL**111**, 242503 (2013).

Constraints on Symmetry Energy (*J* and *L*)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

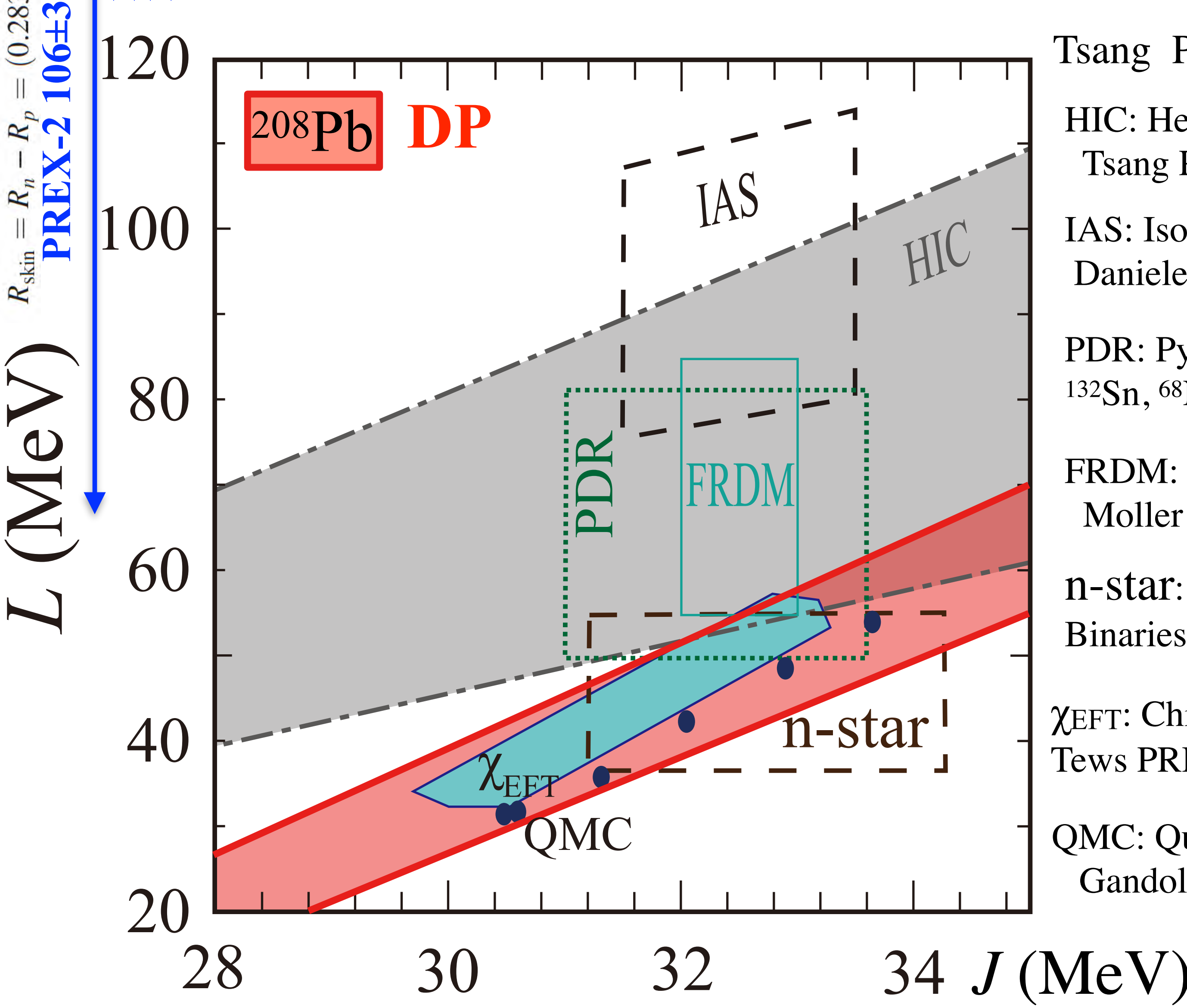
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

Constraints on Symmetry Energy (*J* and *L*)



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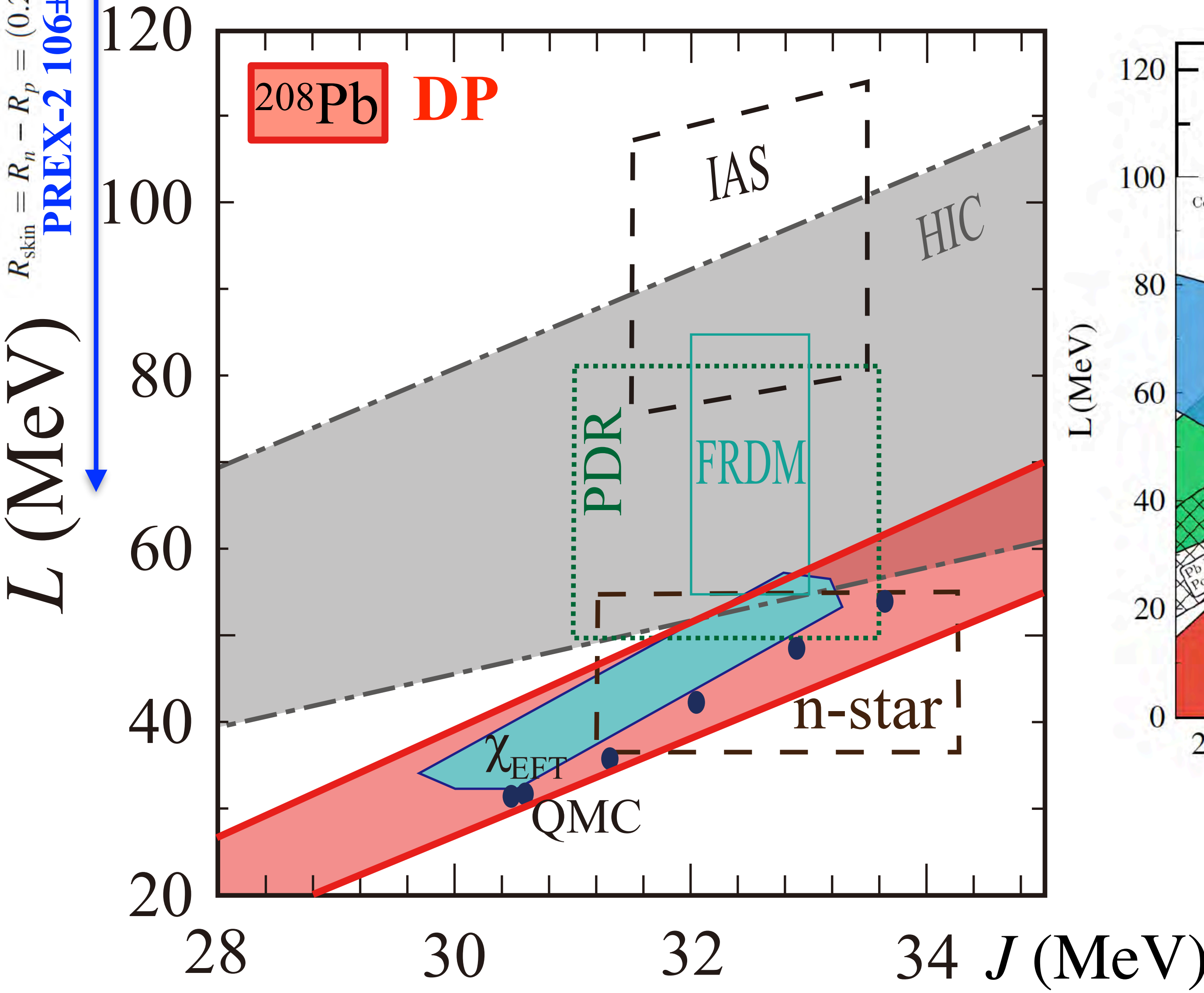
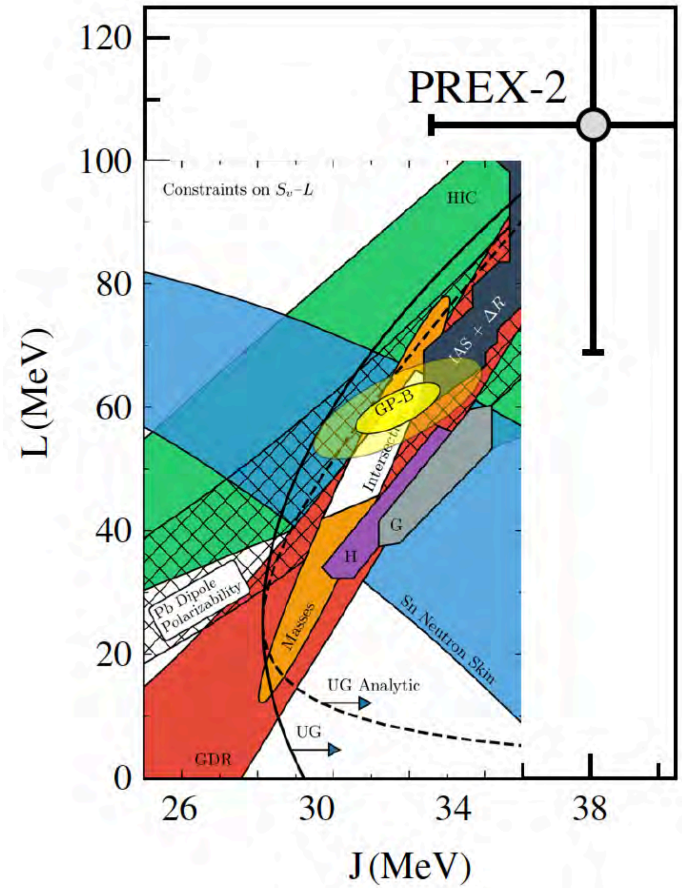
DP: Dipole Polarizability ^{208}Pb AT PRL2011

Constraints on Symmetry Energy (*J* and *L*)

$R_{skin} = R_n - R_p = (0.283 \pm 0.071)$ fm.
PREX-2 106±37 MeV
B.T.Reed et al., PRL2021

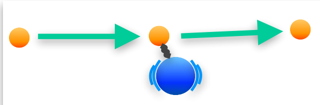


B.T.Reed et al., PRL2021



DP: Dipole Polarizability
^{208}Pb AT PRL2011

Dipole Polarizability of ^{48}Ca

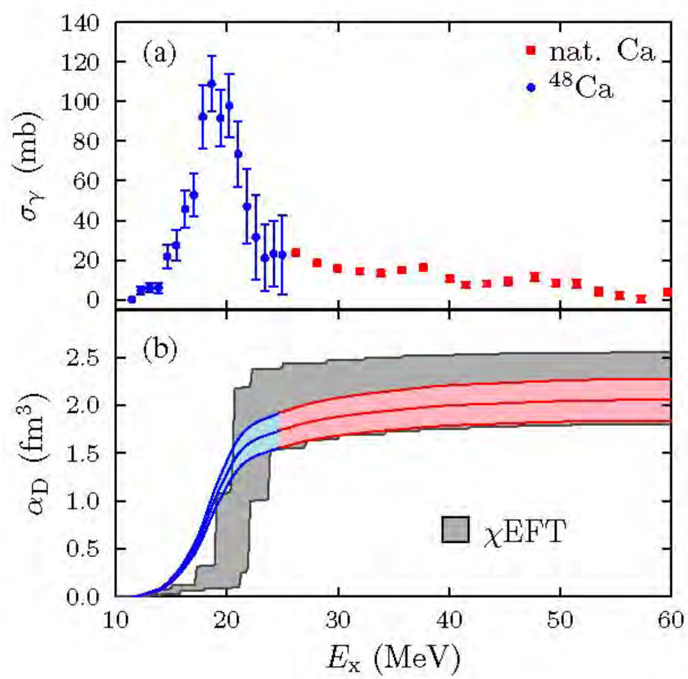


Proton scattering

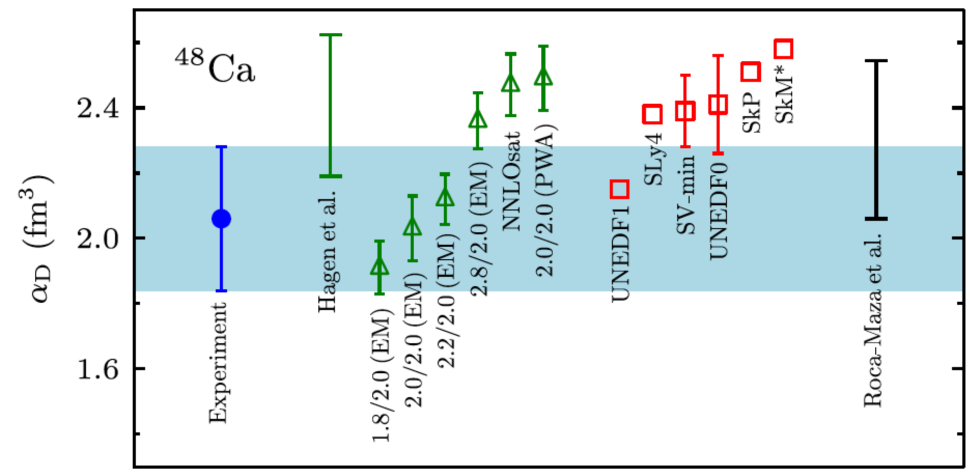
Talk by P. von Neumann-Cosel on Monday

where the EDF and ab-initio calculations meet

Theory: Darmstadt-Tennessee-TRIUMF



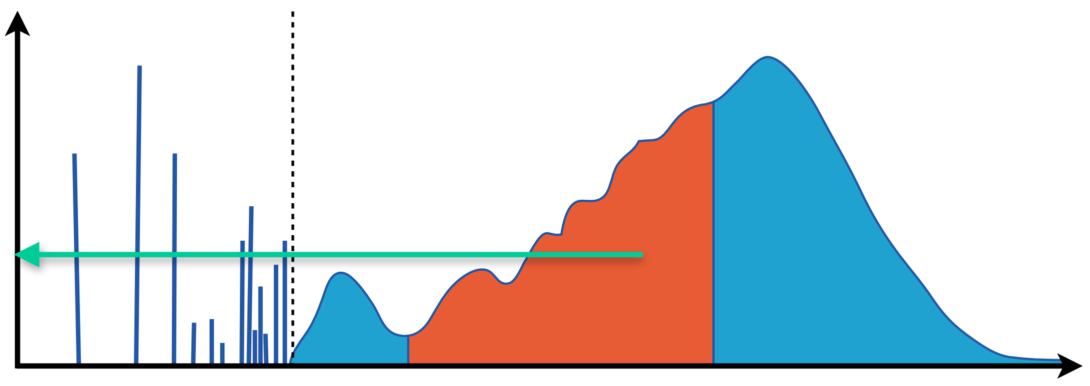
J. Birkhan et al., PRL'17



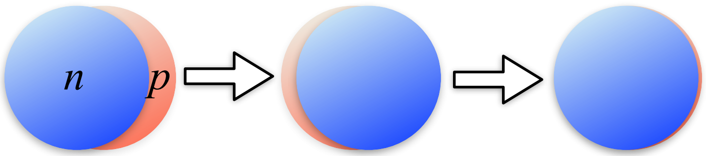
A new measurement is planned for a smaller uncertainty.

ab-initio nuclear structure: plenary talk by S. Bacca on Friday

Gamma Decay of the GDR



Damping Mechanism of Collective Excitations (IVGDR)



Damping of IVGDR

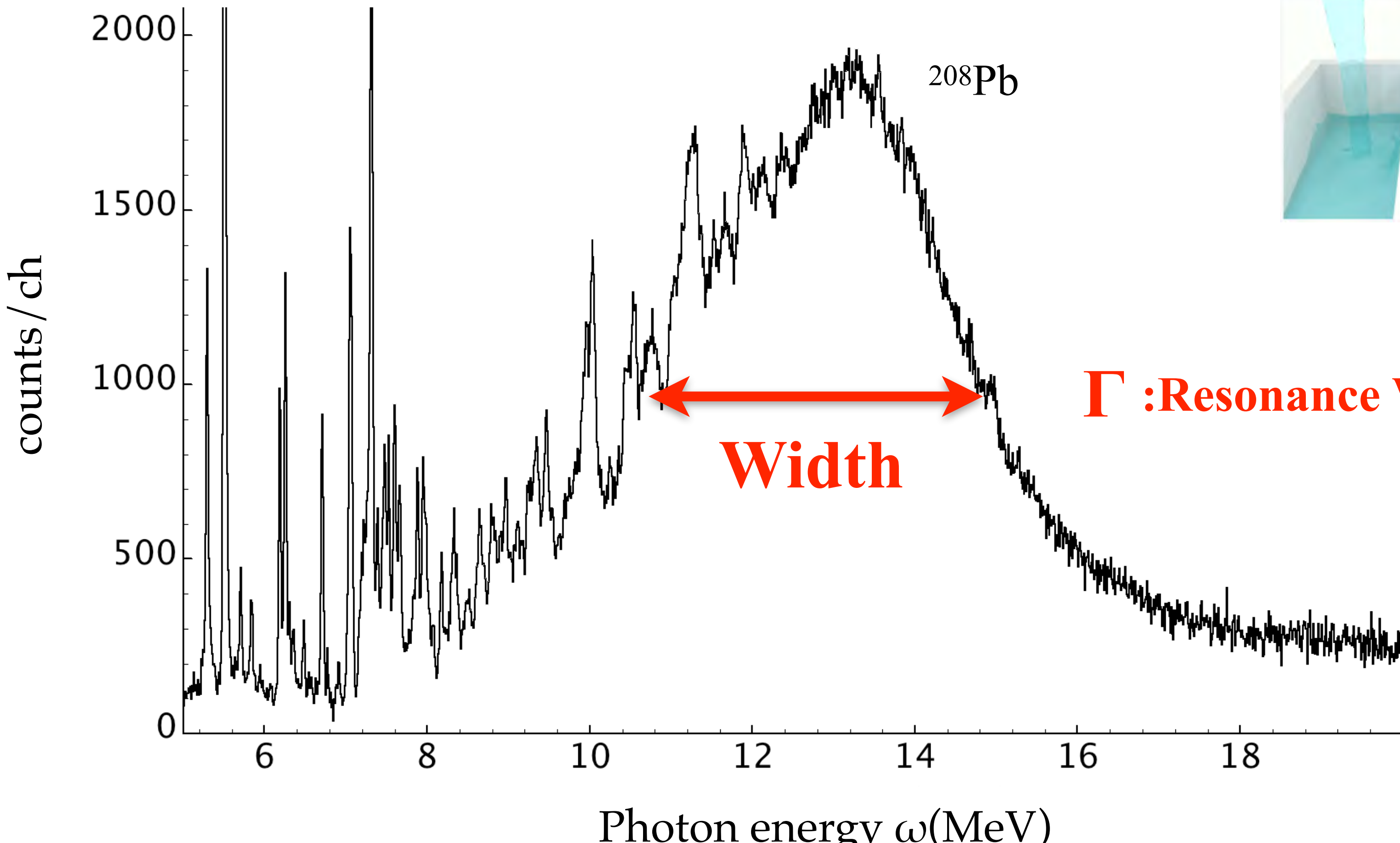
Macroscopically

IVGDR: relative dipole oscillation between *p* and *n*

Damping: due to viscosity between the p and n fluids

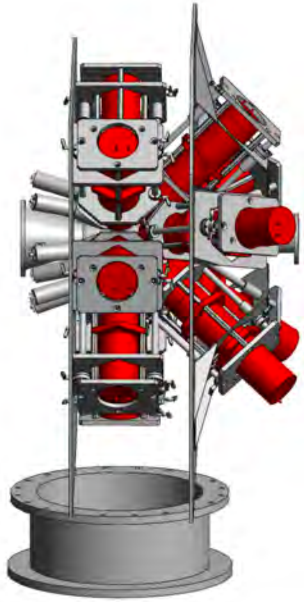
see e.g. J. Wambach, Rep. Prog. Phys.'88

vikipedia



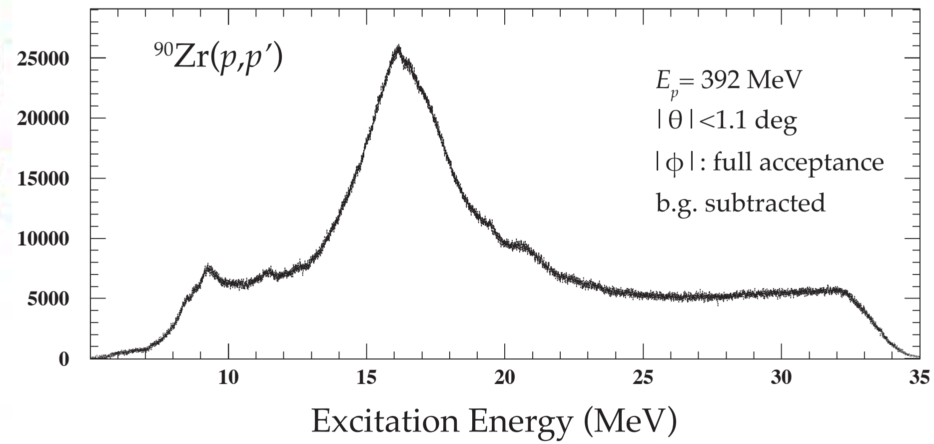
Γ :Resonance Width

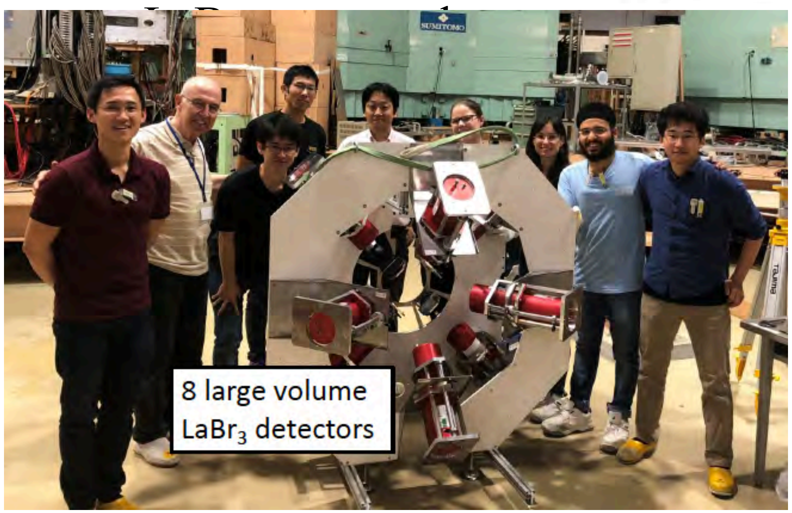
Gamma Decay to the g.s from the GDR in ^{90}Zr



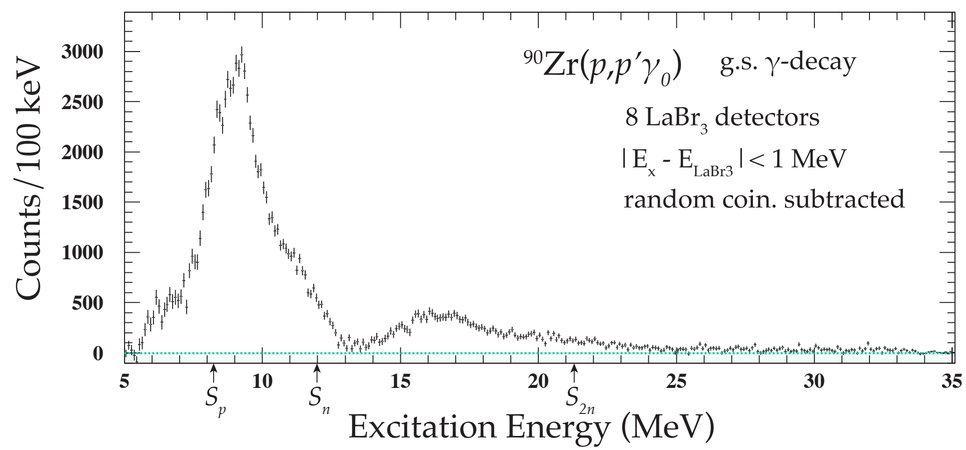
preliminary ^{90}Zr(p,p') at 0 deg

RCNP-E498
semi-offline analysis
2018/08/03 Run #1101-1266





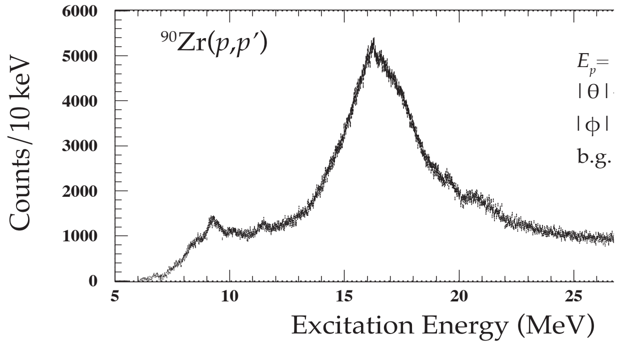
A part of the E498 collaborators
in collaboration with ELI-NP

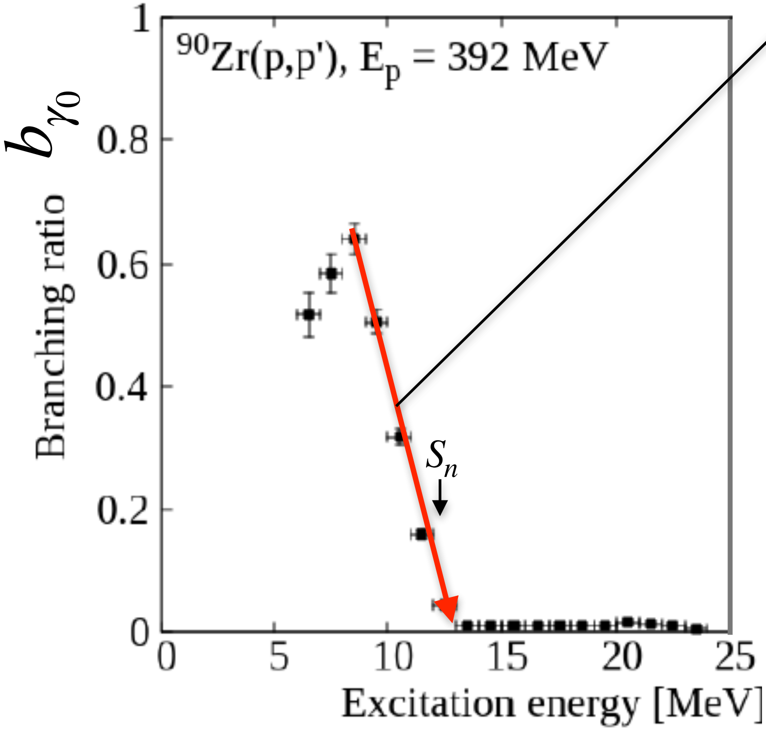


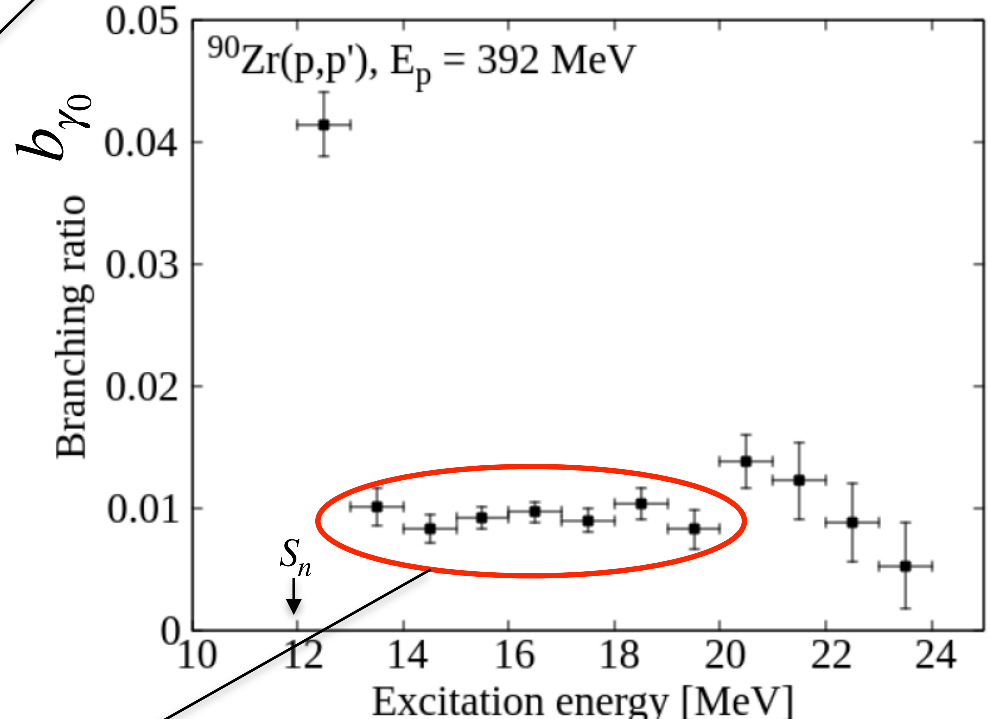
further analysis is in progress

g.s. γ-Decay Branching Ratio

Preliminary







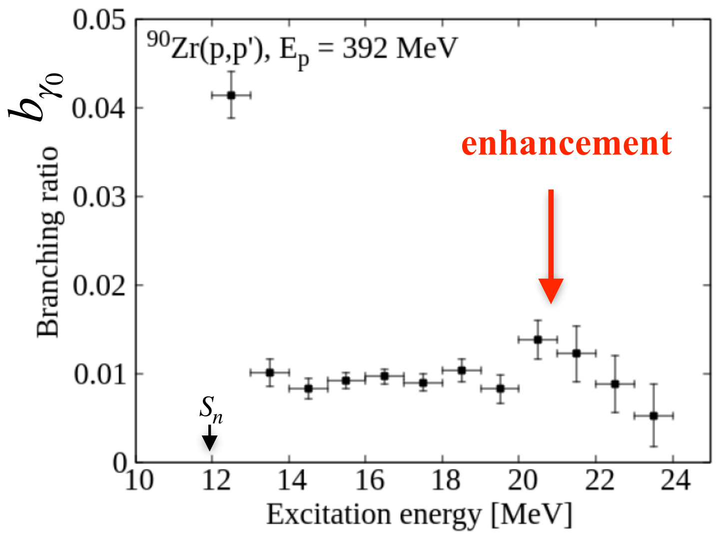
Drop due to increase of cascade γ-decays and the opening of the neutron decay

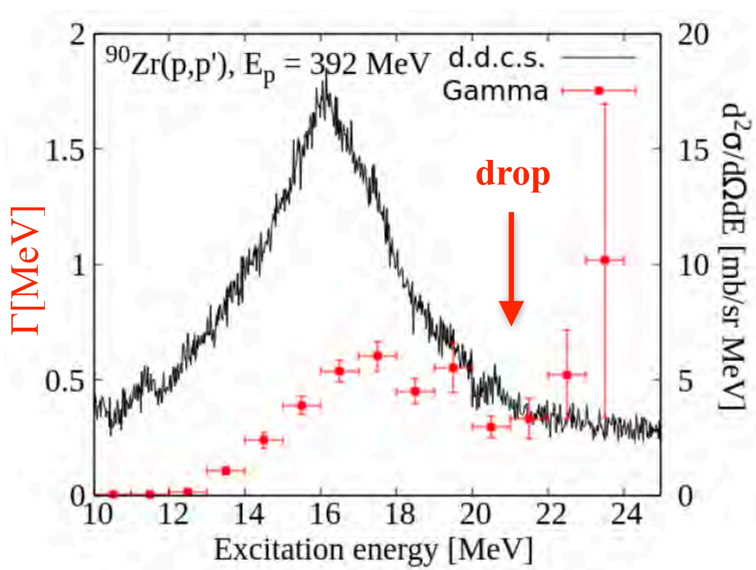
The observed g.s.γ-decay branching ratio is nearly flat in the IVGDR region.

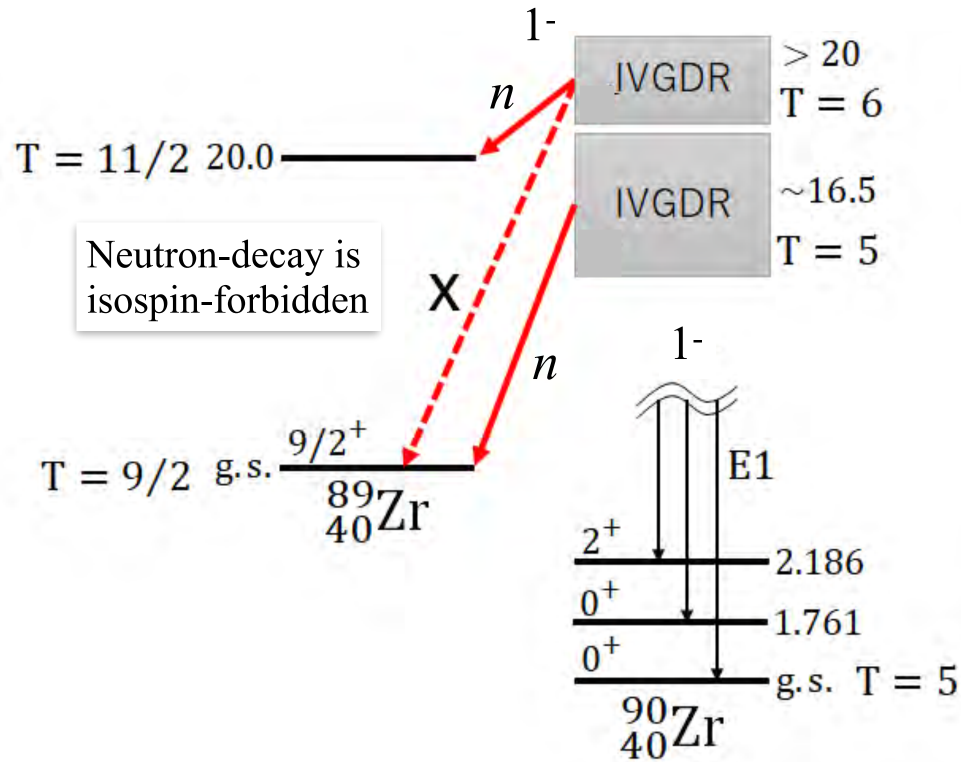
S. Nakamura, master thesis

Effect of the Isospin Upper IVGDR

Preliminary



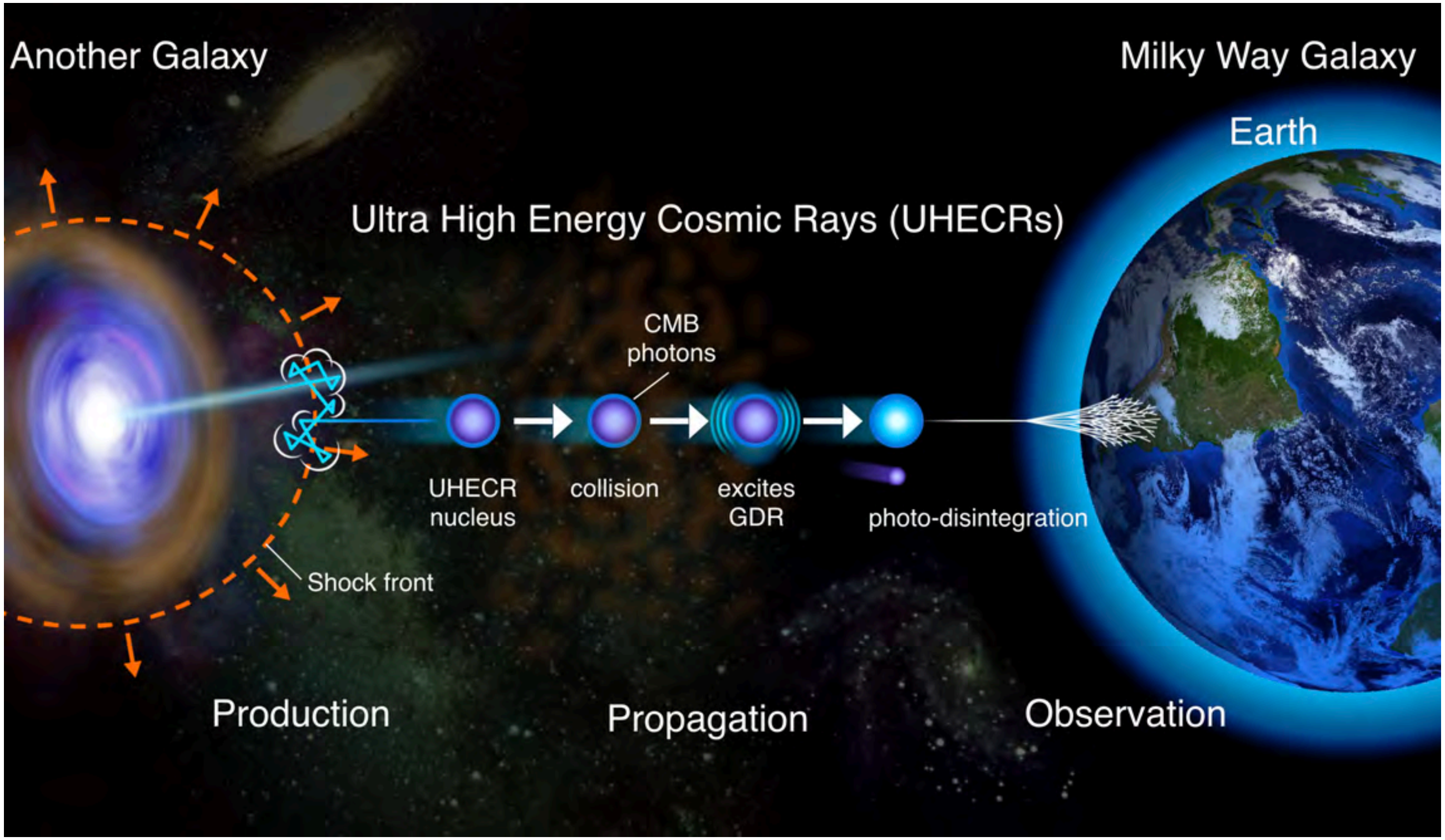




Ex is consistent with the work by ^{89}Zr(p,γ)

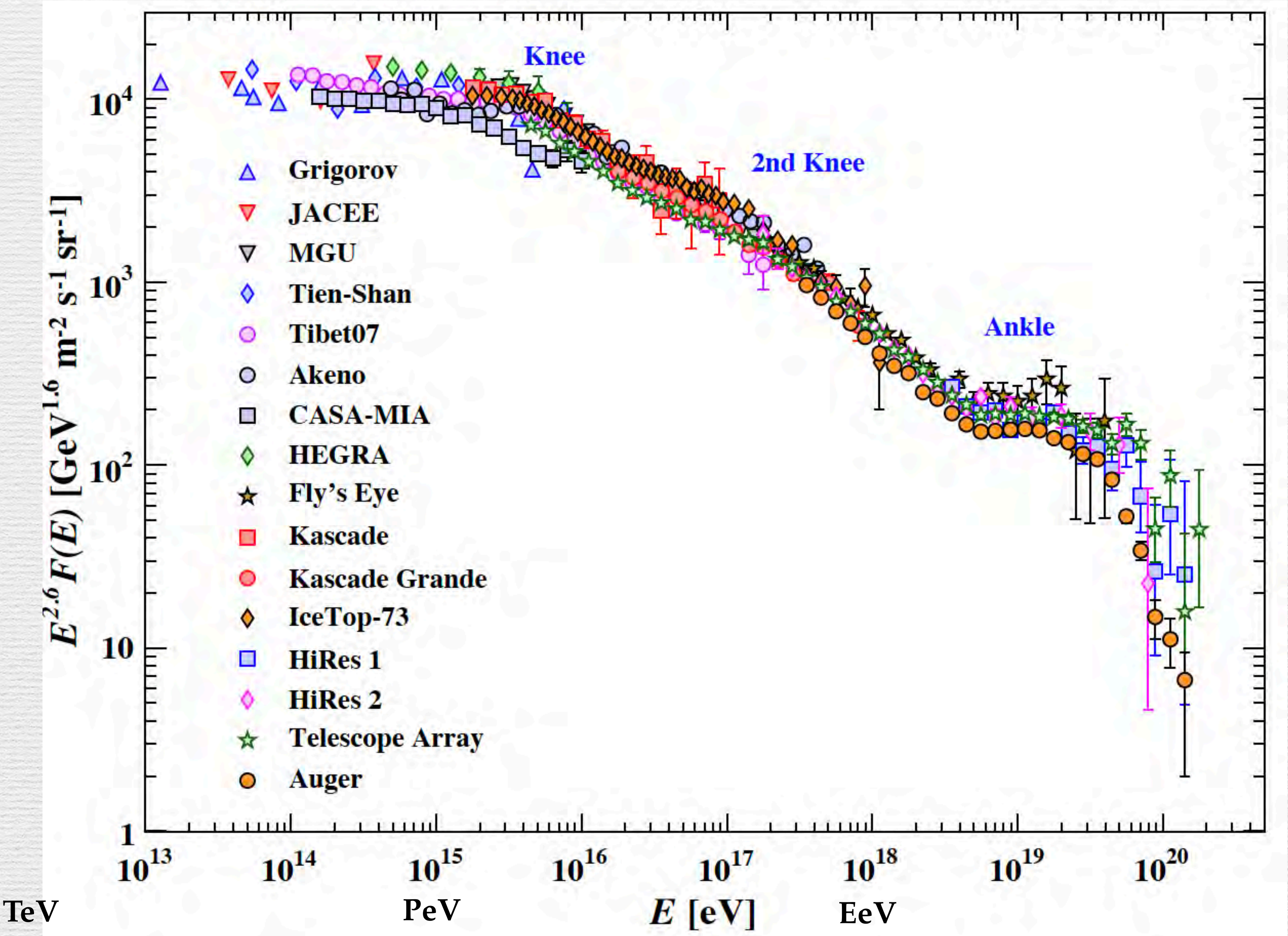
PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

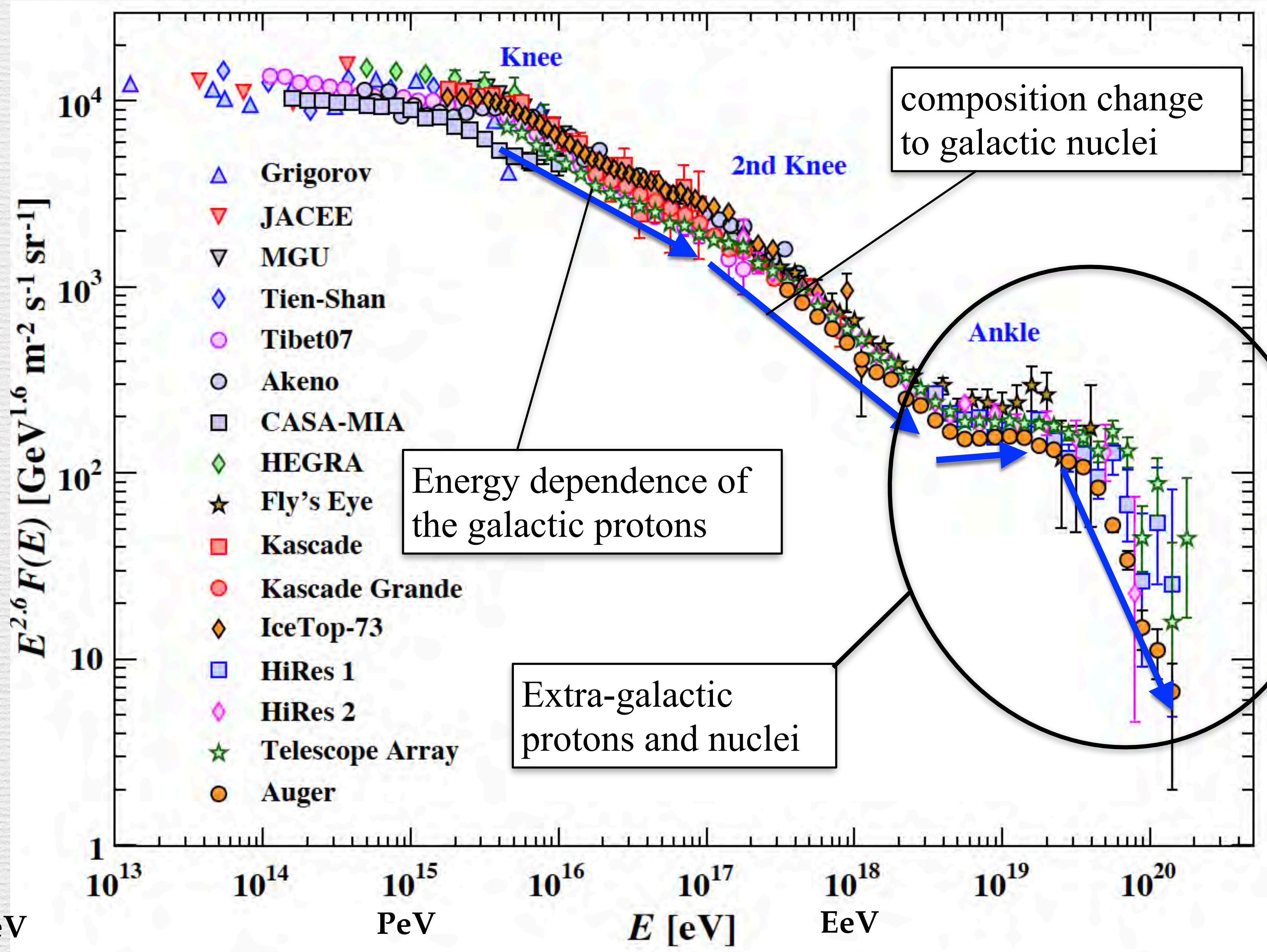


(Ultra-)High-Energy Cosmic Rays

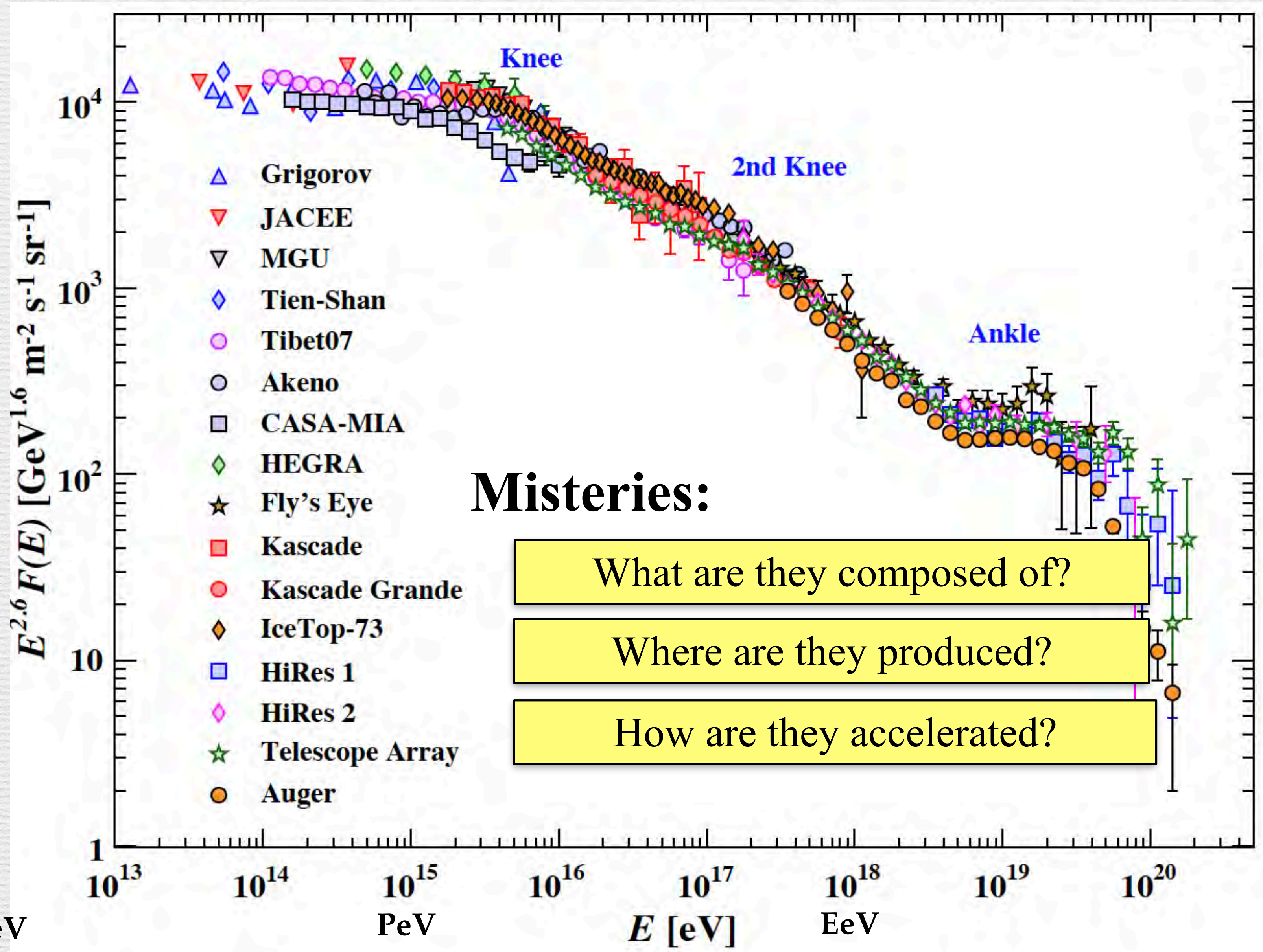
[PDG2018]



Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



Misteries:

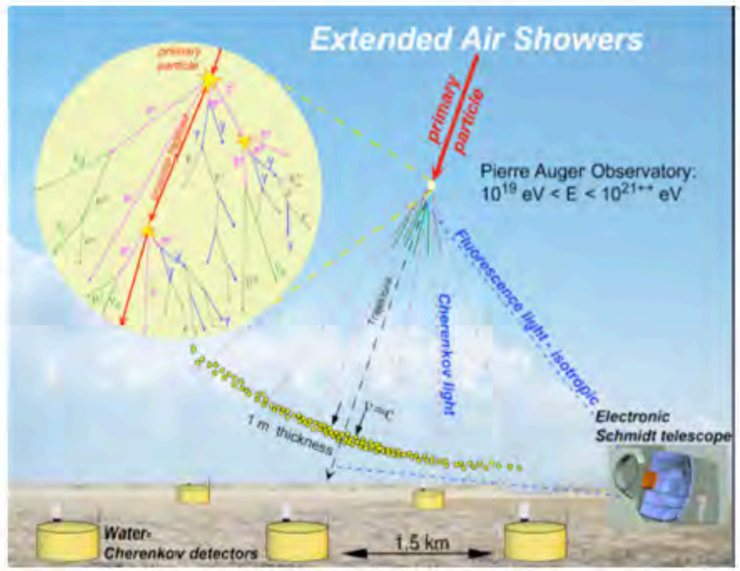
What are they composed of?

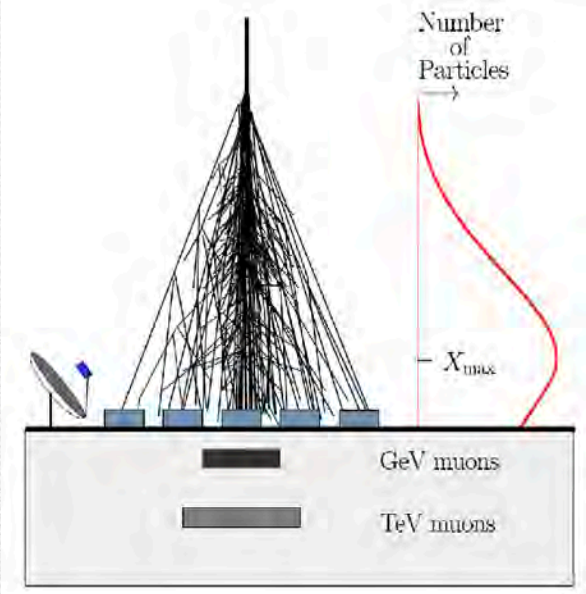
Where are they produced?

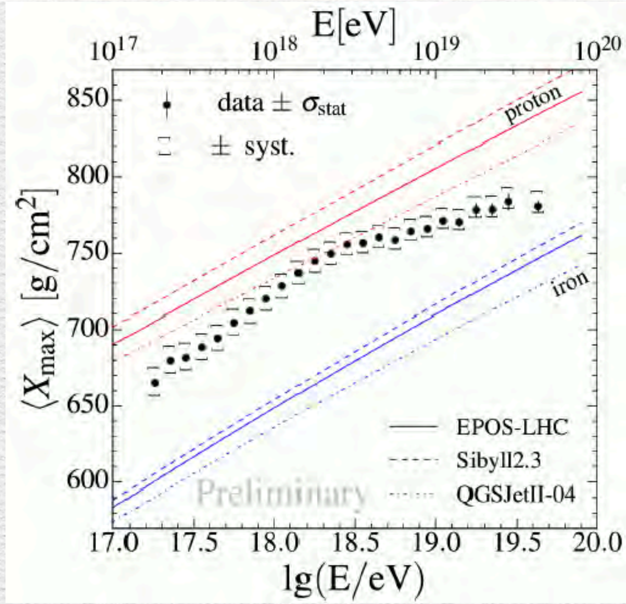
How are they accelerated?

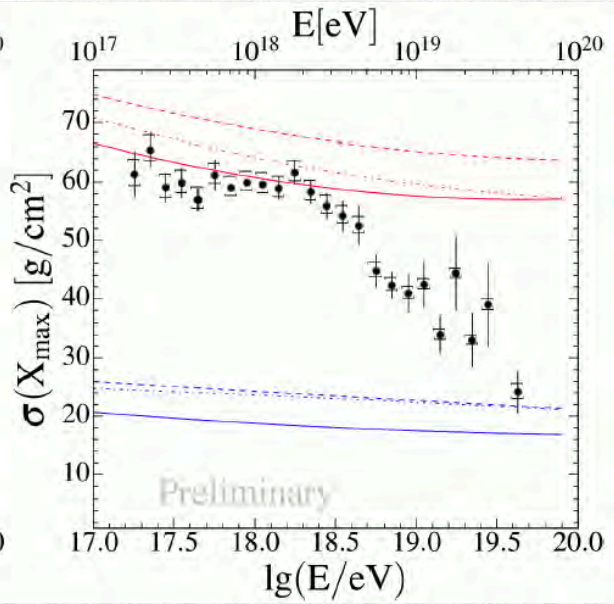
Observation of UHECRs

Extended Air Shower (EAS)





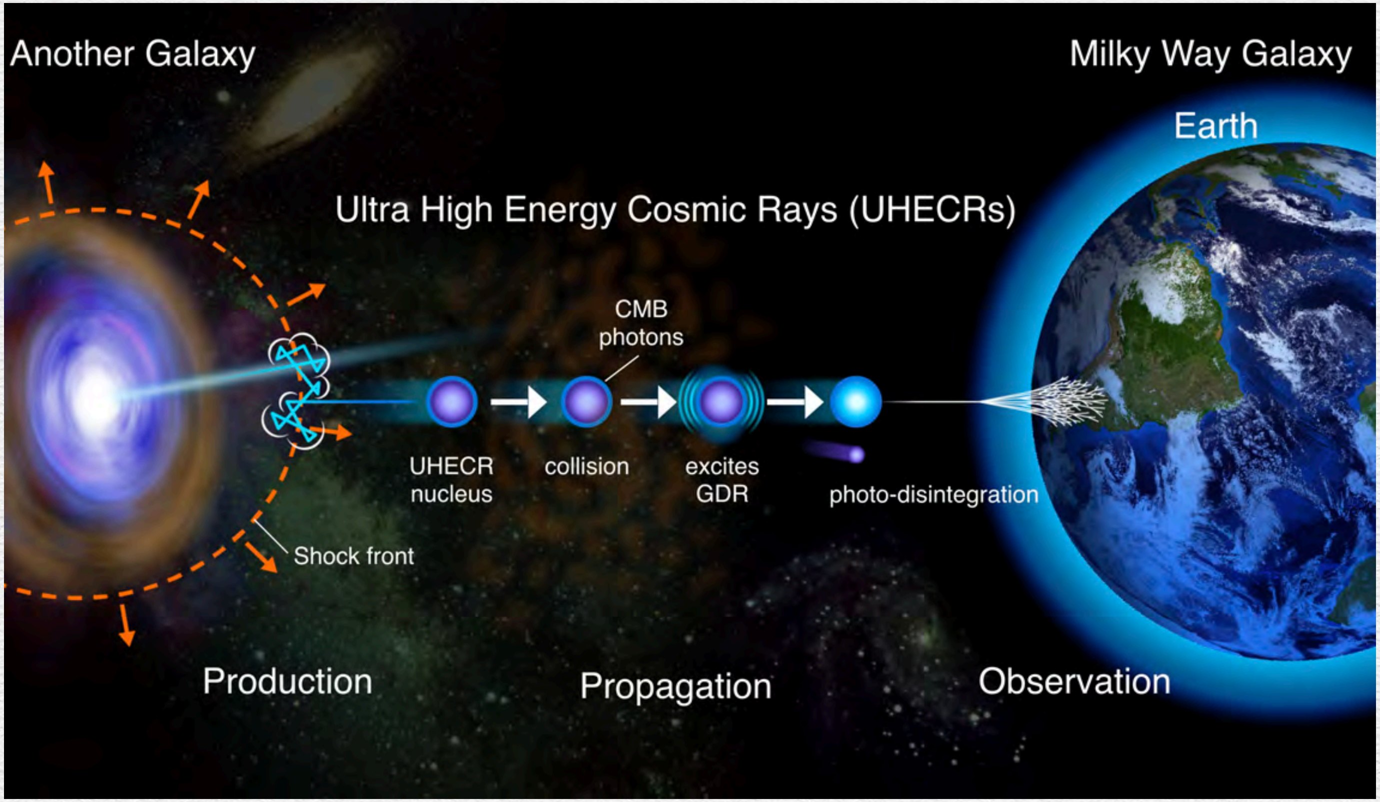




[mol18]
[gor18]

The observed mass tends to become heavier as the energy increase at the highest energy.

Intergalactic Propagation of UHECR Nuclei



Cosmic Microwave Background (CMB)

WMAP
T=2.73 K

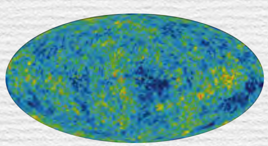
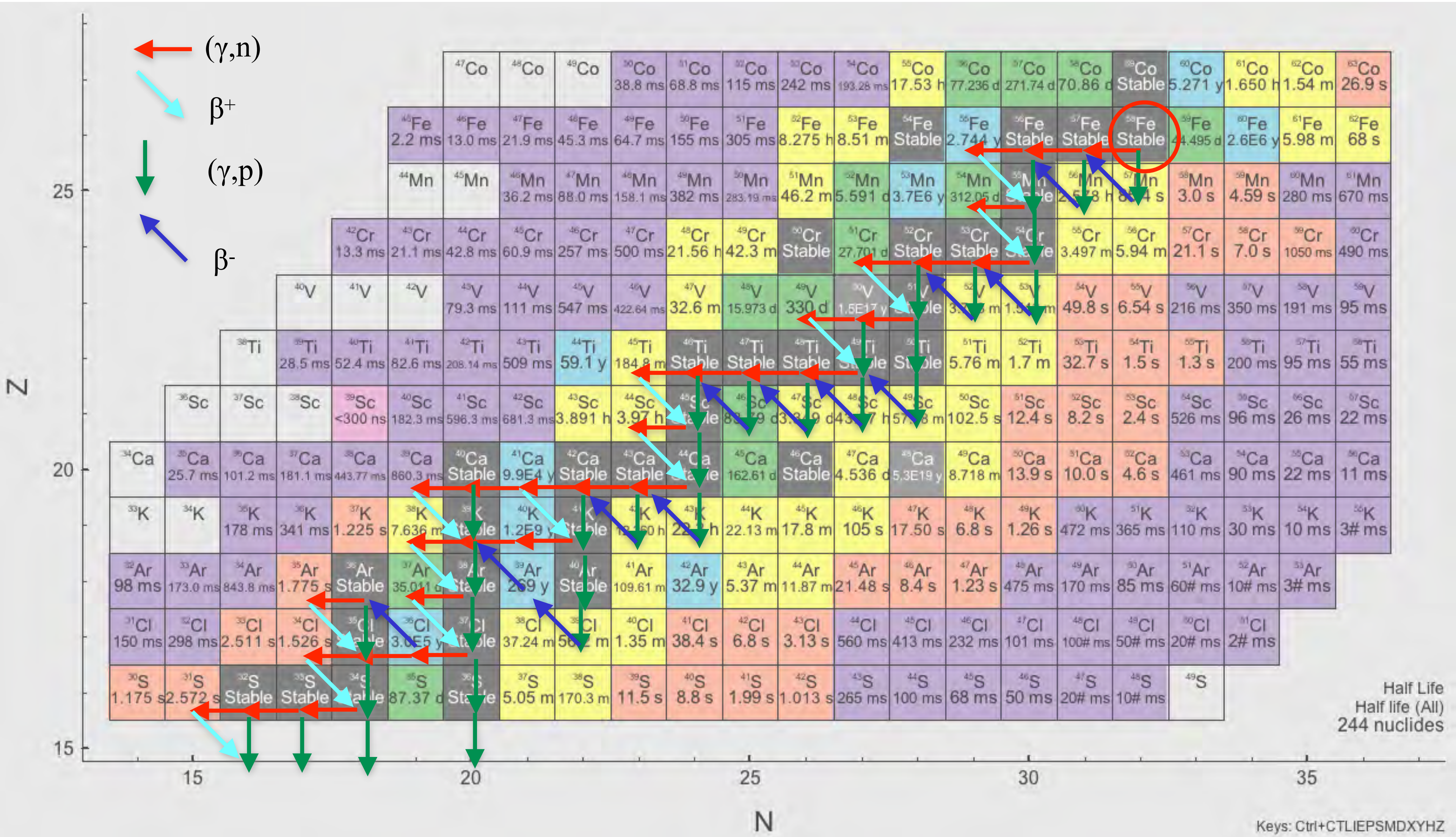


Photo-nuclear reactions determine the allowed travel distance of UHECRs nuclei and their composition/ energy modification in extra-galactic propagation.

GZK cut-off

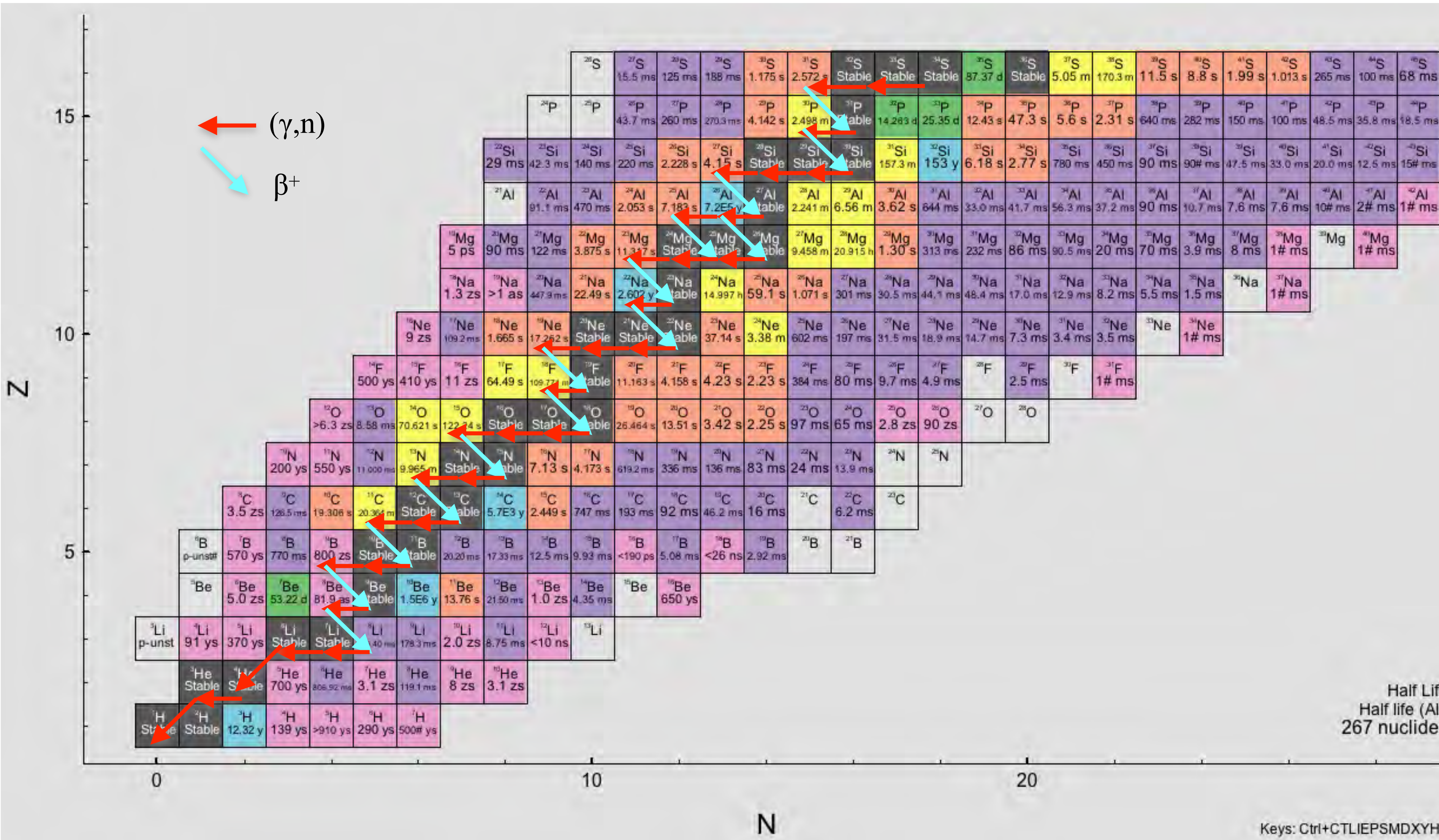
Photo-disintegration Pass of ^{56}Fe



(γ,xn), (γ,α) reactions also take place.

Several unstable nuclei also contribute.

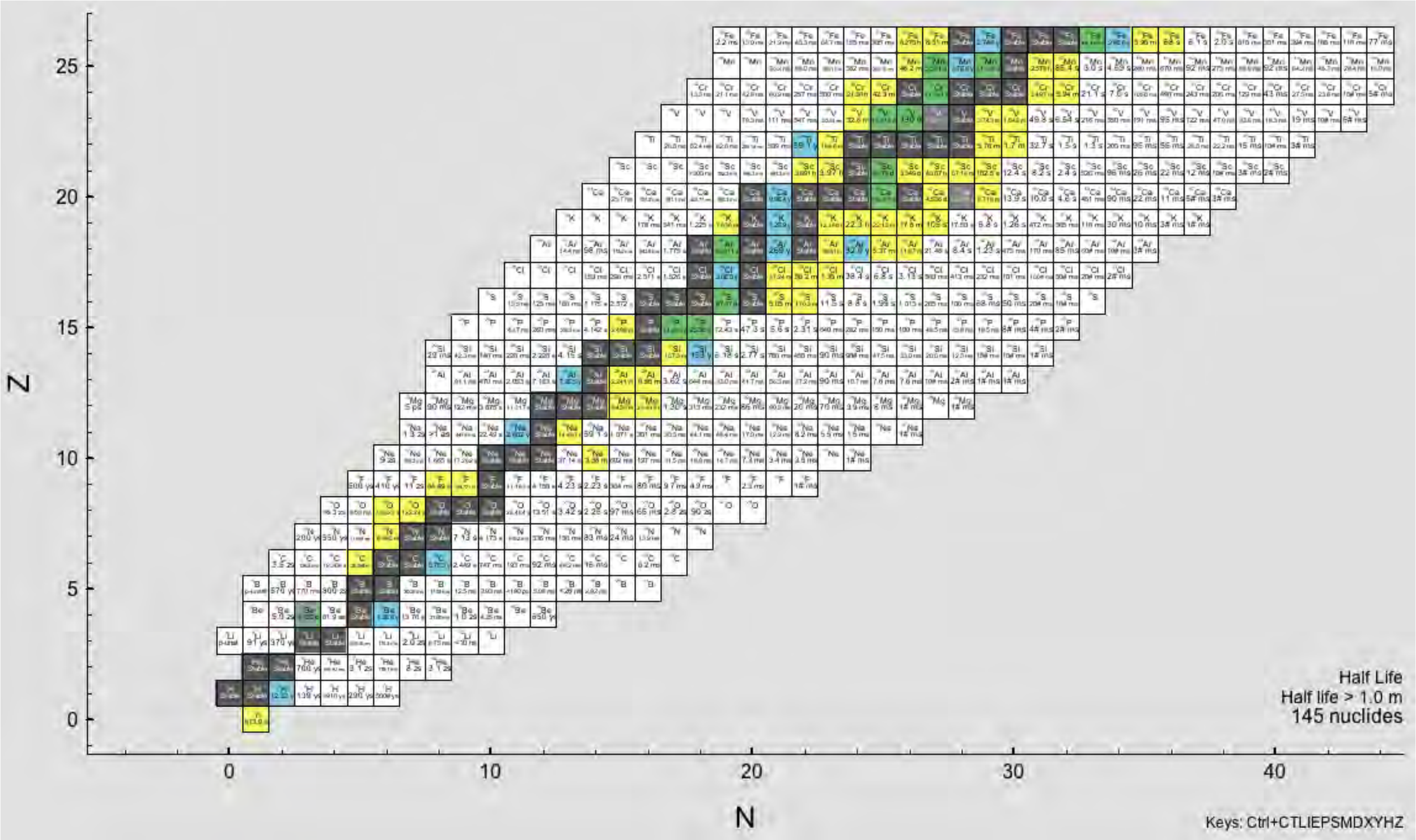
Photo-disintegration Pass of ^{56}Fe



Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

- E1 excitation strength distribution
- n, p, α, γ decay branching ratios

- from light to A~56 for stable nuclei



Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

- E1 excitation stren
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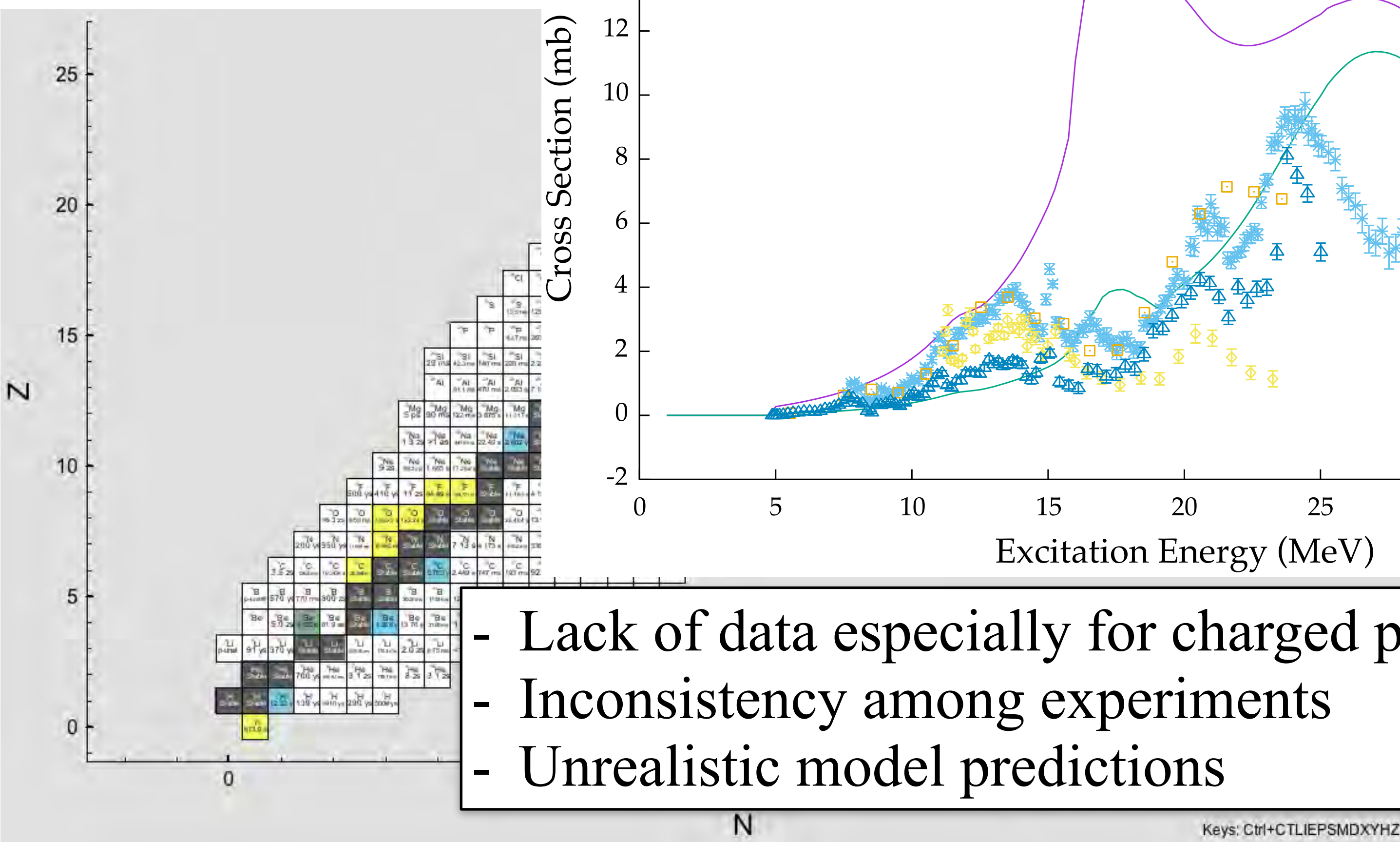
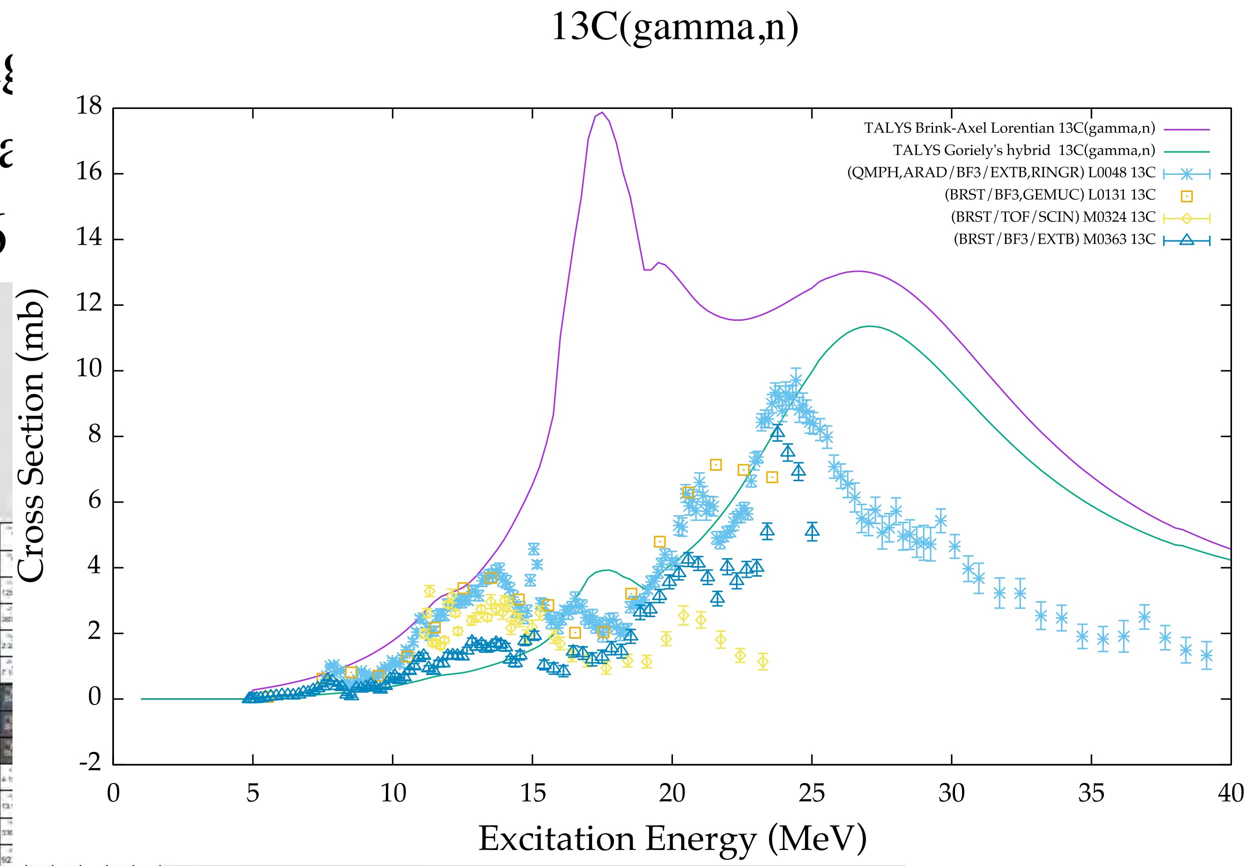
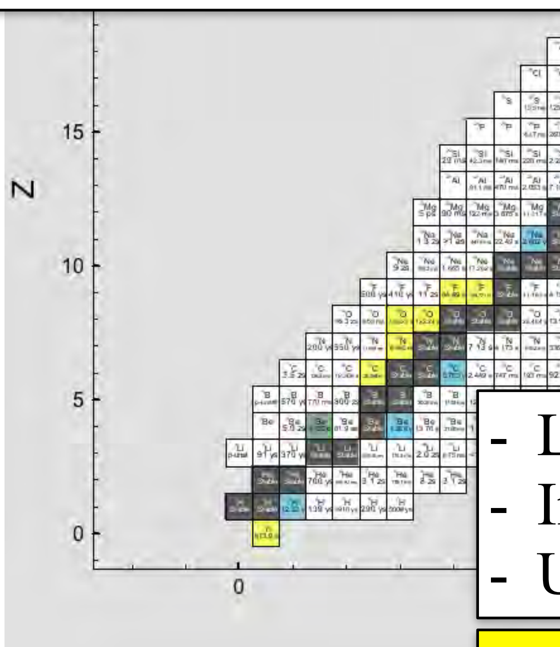


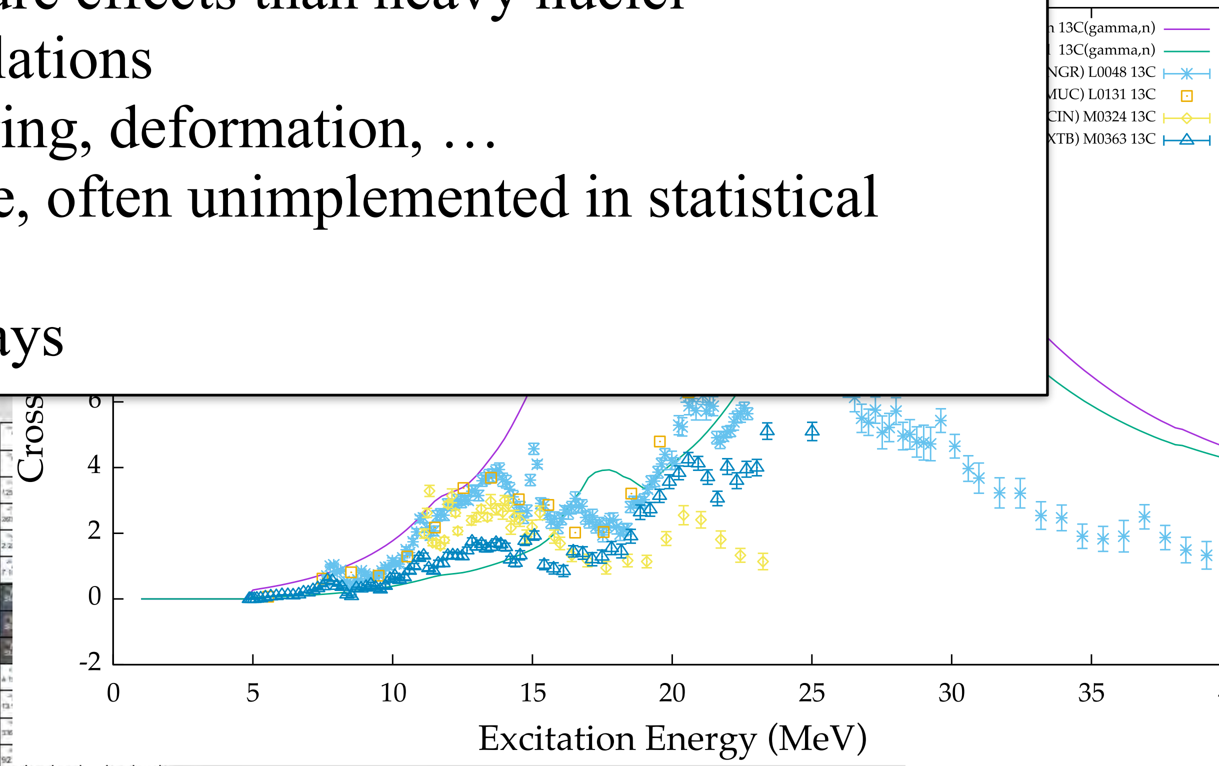


- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

difficulties in theoretical modeling of light-medium mass nuclei
- stronger shell structure effects than heavy nuclei
- many-nucleon correlations
  α-clustering, *np*-pairing, deformation, …
- isospin selection rule, often unimplemented in statistical calculations.
- pre-equilibrium decays





- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

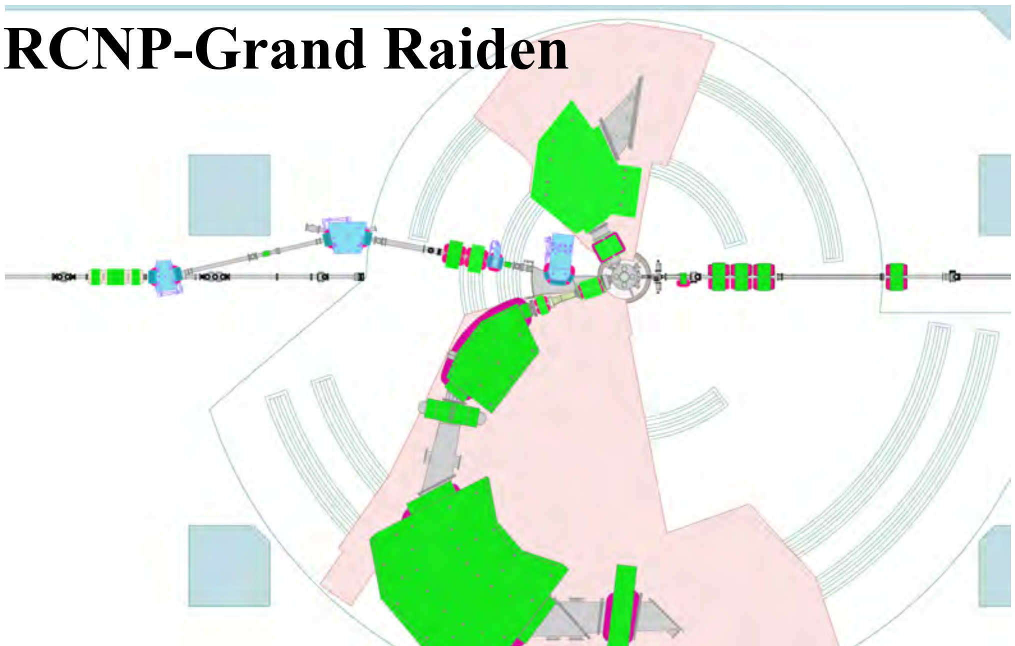
We need good systematic data and reliable models!

PANDORA Project

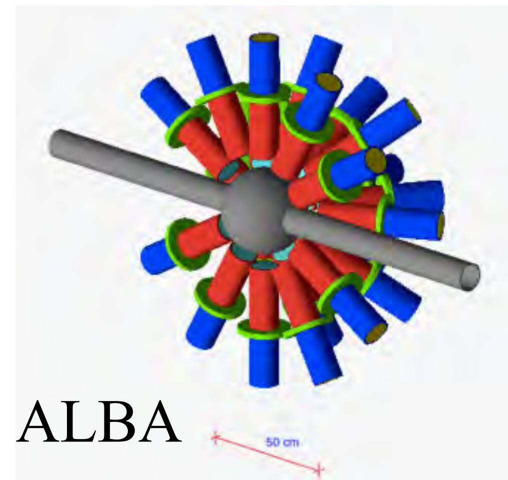
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Systematic Measurement on E1 Strength Distribution and n,p,α,γ decays up to A~56

RCNP-Grand Raiden



iThemba LABS

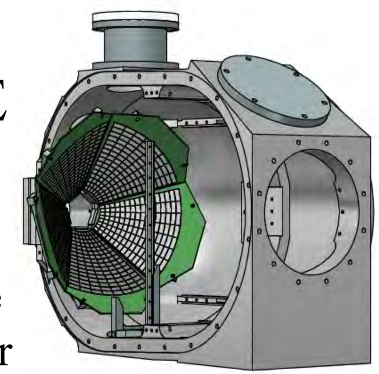


ALBA

ELI-NP

Combination of experiments with complementary devices.

CAKE



decay charge particle detector array

Experiment combining three complementary facilities

Virtual Photon Exp.

iThemba LABS 2022- ^{12}C and ^{27}Al

Total strength distribution up 24 MeV

p,α,γ-decays

multipole decomp. analysis

iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.

L. Pellegri, R. γ, F.D. Smit, J.A.C. Bekker, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, K.C.W. Li, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya

RCNP 2022- (^{10,11}B), ^{12,13}C, ^{24,26}Mg, ^{27}Al

Total strength distribution up 32 MeV

p,α,γ-decays

multipole decomp. analysis

Osaka Univ.

A. Tamii, N. Kobayashi, T. Sudo, M. Murata, A. Inoue, **R. Niina**, T. Kawabata, T. Furuno, S. Adachi, K. Sakanashi, K. Inaba, Y. Fujikawa, S. Okamoto, Y. Fujita, H. Fujita

Real Photon Exp.

ELI-NP 2023-

absolute c.s.

model independent separation of E1 and M1

n,p,α,γ-decays up to 20 MeV

ELI-NP

P.-A. Söderström, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu

PANDORA Project: Collaborator

Nuclear Experiments

RCNP	*Osaka Univ.* **A. Tamii, N. Kobayashi,** T. Sudo, M. Murata, A. Inoue, **R. Niina**, T. Kawabata, T. Furuno, S. Adachi, K. Sakanashi, K. Inaba, Y. Fujikawa, S. Okamoto, Y. Fujita, H. Fujita
ELI-NP	*ELI-NP* **P.-A. Söderström**, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu
iThemba LABS	*iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.* **L. Pellegri**, R. Neveling, F.D. Smit, **J.A.C. Bekker**, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya
TU-Darmstadt	P. von Neumann-Cosel, N. Pietralla, J. Isaak, J. Kleemann, M. Spall
U. Milano/INFN	A. Bracco, F. Camera, F. Crespi, O. Wieland
Shanghai	H. Utsunomiya
U. Oslo	K.C.W. Li, S. Siem, …

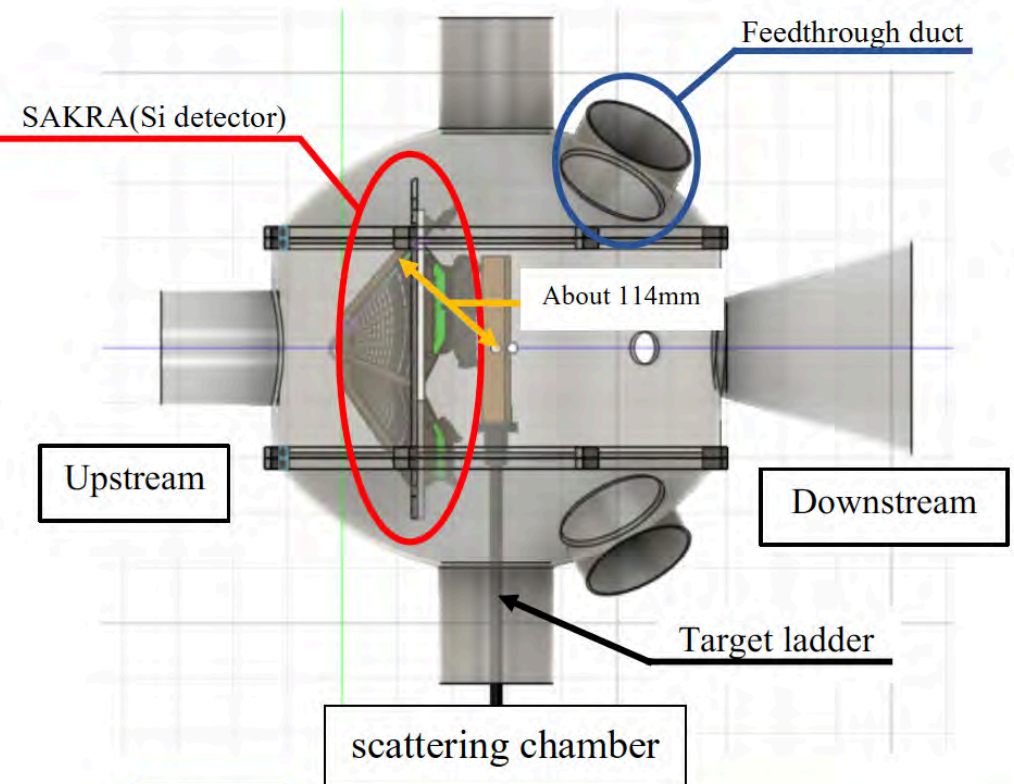
Nuclear Theory

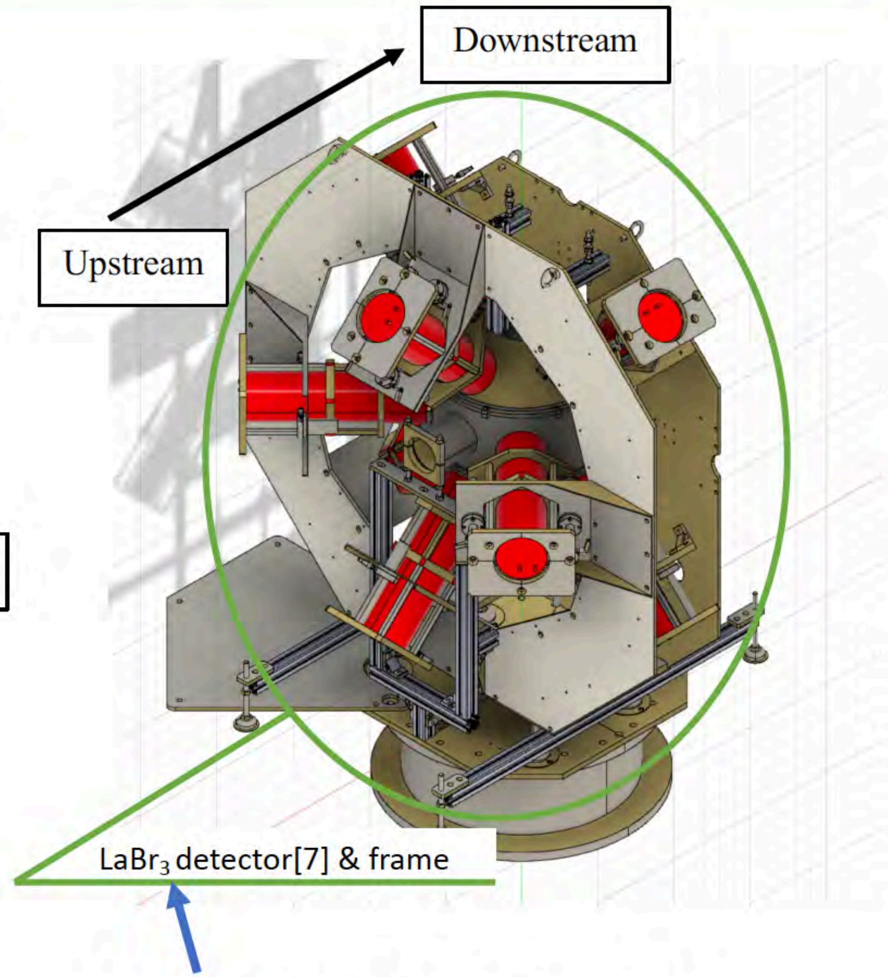
AMD	**M. Kimura, Y. Taniguchi**, H. Motoki
NRFT	**E. Litvinova**, P. Ring, H. Wibowo
RPA/DFT	RPA by **T. Inakura, QPM by N. Tsoneva**
TALYS	**S. Goriely**, **E. Khan**
Large Scale Shell Modle	Y. Utsuno, N. Shimizu

UHECR Theory

Propagation and production	**D. Allard**, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff **S. Nagataki**, **E. Kido**, J. Oliver, H. Haoning

Features of this scattering chamber



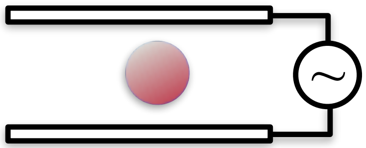


Features

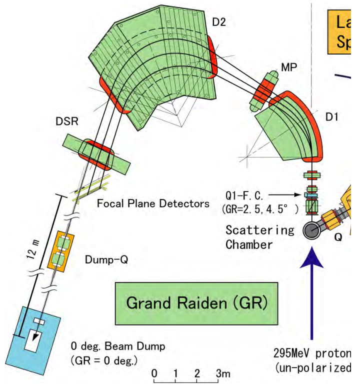
- Near Spherical shape
  → To bring the detector closer
- SAKRA mounted on lid
  →For easy SAKRA evacuation

This $LaBr_3$ detectors belongs to the Milan Group.

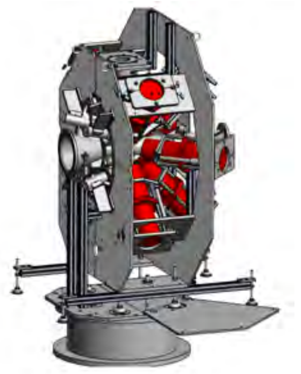
Summary



I. Electric Dipole Response of Nuclei

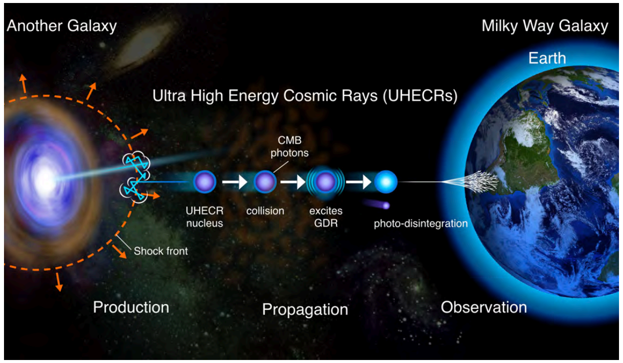


II. Experimental Methods



III. Topics

- Polarizability and Symmetry Energy
- Gamma Decay of GDR
- PANDORA project
  Ultra-High-Energy Cosmic Rays



Thank you

for your attention